Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology

Sindre Kolbjørnsgard

Analysis of Arctic shipping operations using enhanced historical AIS data

Master's thesis in Department of Marine Technology
Supervisor: Ekaterina Kim, Bjørn Egil Asbjørnslett, Morten Mejlaender-Larsen
Co-supervisor: Nabil Panchi

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Preface

This master thesis was carried out during the spring semester of 2022 at the Norwegian University of Technology and Science (NTNU), Department of Marine Technology.

I would especially like to thank my supervisor, Associate Professor Ekaterina Kim (NTUN), for her excellent guidance, the useful discussion throughout the semester, and support throughout the academic process. Her insight has helped me understand the problem of operations in the Northern sea route. I would also like to thank Morten Mejlaender-Larsen (DNV), Ph.D. Candidate Nabil Panchi (NTNU) and Professor Bjørn Egil Asbjørnslett (NTNU) for helping with data-related discussions, formulation, and sharing their knowledge about the maritime industry in the Arctic.

Last but not least, I also want to thank other students, friends, and family for discussions, general feedback, and loads of fun during the five years at NTNU.

Trondheim, June 9, 2022

Sindre Kolbjørnsgard

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Summary

Today´s challenges for the sustainable development of the maritime industries in harsh environments include maintaining competitiveness globally, optimizing energy sources, and minimizing their environmental impacts. International Maritime Organization (IMO) recommends POLARIS as an acceptable methodology to determine a set of operational limitations in ice. Despite limitations, POLARIS is “a pillar in the overall decision process of various stakeholders such as classification societies, underwriters, and shipowners” (1). The RIO can be calculated from available data, and a vessel's operability can be determined. POLARIS can be used for two primary purposes (planning or an onboard tool). However, experience from POLARIS users is limited. In this view, the main objective of this thesis has been to address the following research question: *to which degree can POLARIS, based on available ice information, be used for planning purposes?* The thesis was based on a collaboration between Det Norske Veritas (DNV) and the Institute of marine technology (IMT). DNV provided four meetings and access to an expert on POLARIS and operations under the polar code.

This master thesis presents a methodology for assessing operational risk based on historical and available data. In the first part of this thesis, a validation study of relevant data input for ice conditions, AIS data, and ice classes was conducted. This part was considered essential to determine to which degree POLARIS can be used for planning purposes. In the second part, RIO calculations based on historical data were presented. Vessels with lower ice classes were in 99,45% of the AIS messages collected operating within their RIO limits. This work established a link between the operational risk, the number of days to the closest ice chart, and speed based on RIO calculations from the developed model. In the last part, a predictive method for forecasting a vessel's operational limitations for a given week was developed based on a historical AIS route and ice charts. First, the most challenging areas were established based on median RIO values for a whole year. Second, the operational limits for the freezing period for different ice classes were investigated, and a forecast for when a vessel with a given ice-class could operate with or without an ice breaker was established. Lastly, the operational limitations for each week were analyzed by investigating how much of the route a specific operational limitation could be expected.

Sammendrag

Dagens utfordringer for en bærekraftig utvikling av den maritime næringer i Arktisk inkluderer å opprettholde konkurransefortrinne globalt, optimalisere energikilder og minimere den totale miljøpåvirkning. International Maritime Organization (IMO) anbefaler POLARIS som en akseptabel metodikk for å bestemme og sett operasjonelle begrensninger i is. Til tross for flere begrensninger, er POLARIS i dag «en pilar i den overordnede beslutningsprosessen til ulike interessenter som klasseselskaper, kapteiner og redere» (1). RIO kan beregnes fra tilgjengelige data, og et fartøys operabilitet kan bestemmes. POLARIS kan brukes til to primære formål (planlegging eller som et beslutningsverktøy ombord). Erfaring fra POLARIS som et planleggingsverktøy er imidlertid begrenset. Hovedmålet med denne oppgaven har vært å studere følgende forskningsspørsmål: i hvilken grad kan POLARIS, basert på tilgjengelig isinformasjon, brukes til planleggingsformål? Oppgaven var basert på et samarbeid mellom Det Norske Veritas (DNV) og Institutt for marin teknologi (IMT). DNV var med på fire møter og ga tilgang til en ekspert på POLARIS og operasjoner under polarkoden.

Denne masteroppgaven presenterer en metodikk for å vurdere operasjonell risiko basert på historiske og tilgjengelige data. I den første delen av denne oppgaven ble det gjennomført en valideringsstudie av relevante datakilder for isforhold, AIS-data og isklasser. Denne delen ble ansett som vesentlig for å bestemme i hvilken grad POLARIS kan brukes til planleggingsformål. I andre del ble RIO-beregninger basert på historiske data presentert. Fartøyer med lavere isklasser var i 99,45 % av AIS-meldingene som ble samlet inn innenfor deres RIO-grenser. Denne delen av arbeidet etablerte en sammenheng mellom operasjonell risiko, antall dager til nærmeste iskart, og hastighet basert på RIO-beregninger fra den utviklede modellen. I siste del ble det utviklet en prediktiv metode for å forutsi et fartøys operasjonelle begrensninger for en gitt uke basert på en historisk AIS-rute og iskart. Først ble de mest utfordrende områdene beregnet basert på median RIO-verdier for et helt år. Videre ble operasjonsperioden i perioden der NSR fryser til bestemt for ulike isklasser, og det ble etablert en prognose for når et fartøy med en gitt isklasse kunne operere med eller uten isbryter. Til slutt ble driftsbegrensningene for hver uke analysert ved å undersøke hvor mye av ruten en spesifikk isklasse kunne forvente å måtte bruke isbyter, kunne operere fritt eller ikke opperere.

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1 Introduction

Over the past 49 years, the Arctic has warmed three times faster than the global annual average. Strong evidence shows that there has been an increase in rapid sea ice loss events together with an increase in extreme events. As a result of climate change, sea ice in the arctic declined by 43% between 1979 and 2019. As a result, there has been a change in Arctic maritime activities, which are now rapidly growing because of better technology and less sea ice. Today's challenges for the sustainable development of marine industries in harsh environments include maintaining competitiveness globally, optimizing energy sources, and minimizing their environmental impacts.

According to IMO, maritime activity is expected to grow further in volume and density. New shipping routes are already developing in new harsh, vulnerable, and remote polar areas. New approaches for evaluating risks posed to a vessel must be developed to address the risks and challenges in the arctic waters. The combination of poor weather, lack of adequate communications systems, charts, and good information about the historical data, combined with the challenges of performing rescues and ocean cleanups in these areas, makes them both vulnerable and challenging. The Polar Code was developed by the International Maritime Organization (IMO) and entered into force on 1 January to maintain an acceptable level of risk under polar operations. The polar code is an International Code for Ships Operating in Polar Waters, and it covers design, training, searches and rescue, environmental protection, construction, and equipment. The early approaches primarily related ice-classto a maximum ice thickness. These approaches typically assume 100% ice concentration. However, 100% concentration of level ice of one ice type is rarely encountered in real life.

IMO proposes the Polar operational limit assessment risk indexing system (POLARIS), an approach for determining limitations for operation in ice, which can be used by admiNICtration and masters to understand better the risk related to operations in the arctic. According to IMO is POLARIS an acceptable methodology to determine a set of operational limitations in ice. Despite limitations, POLARIS is “a pillar in the overall decision process of various stakeholders such as classification societies, underwriters, and shipowners” (1) POLARIS combines ice-class from the Polar Code with ice conditions defined in the EGG Code by the WMO. POLARIS is a decision support system that considers both the ice-class of the ship and the encountered ice conditions when determining the risk (2) (3).

1.1 Objective

The main objective of the present master is to develop a method to investigate the following research question: *to which degree POLARIS, based on available ice information, can be used for planning purposes?* More specifically, how can POLARIS be used for planning purposes for cargo shipping with lower ice classes and transit operations in the Northernsearoute. This thesis includes a detailed study of the operational risk picture for operation in the NRS according to POLARIS, benchmark and validation of the relevant data sources that could be used in an analysis related to POLARIS. Furthermore, situations, where it is possible to extend the operational season for low ice-class vessels and identify needs for IB assistance are also of extra interest.

The thesis aims to develop a methodology and a model where POLARIS is used as a tool to plan transit voyages for vessels with lower ice classes. Ideally should, open-access data be used if this is possible. There is also essential to validate the relevant input data and understand the data limiting the model. The final result should also be compared to relevant sources and studies to validate the model.

1.2 Publications using POLARIS in the arctic region

Relevant literature was collected using keyword search across different databases such as Oria, google scholar, and web science. As a result, these five articles discuss the risk for vessels operating in the arctic region. An overview of papers describing risk analysis methods in the arctic region from 1970 to 2021 describes 29 studies and their methods in detail (4). The study addresses the shortcoming of comprehensive and systematic reviews of the existing models. It is especially relevant to highlight the increase in new models and how ships operate in the arctic regions. The method presented in this thesis will use POLARIS, and the findings related to this are therefore of extra interest. The study addresses the limitations of POLARIS, where the most important is that POLARIS does not consider the experience of the captain, ice compression, and the presence of ice ridges and icebergs, which may affect the safety of operations. It also mentions the challenges when POLARIS does not account for vessel type and only considers the ice class. Therefore, the risk index does not reflect the full risk picture concerning the consequences of an accident. Another limitation of POLARIS, as noted by (Fedi et al., 2018), is that it does not explicitly consider human factors.

The literature regarding POLARIS in the arctic region can be divided into the Northwest passage(NWP) or the Northern sea route(NSR). The NSR has been studied in more detail than the Northwest passage. For the NSR and Svalbard, one overview study and x specific case studies focusing on POLARIS in the arctic. The overview study reviews and compares existing risk analysis models applied to shipping in ice-covered waters (1). The three specific publications compare traffic limitations in the Kara Sea: Do vessels remain within their operational limitations in ice? Analyzing the risk of vessels operating in the Kara Sea region using POLARIS, and how safe were vessels during research cruises in the Arctic in 2007-2019? This study links the ice condition to position data, where POLARIS is used to investigate the risk picture. The two publications mentioned last are most relevant for this project and have a similar method and approach for combining historical data to calculate the RIO. However, it is limited to a smaller area and is not considering the whole NSR or transit. These studies are also limited to analyzing historical operations.

In 2020 a paper was published about mapping and analysis of maritime accidents in the Russian Arctic through the Polar Code and POLARIS system lens. This study analyzes the RIO for three different accidents in the NSR. Two out of three accidents happened with a positive RIO. The vessel was sailing in the White Sea when it sustained damage following contact with ice. According to the POLARIS RIO, the vessel has experienced favorable operating conditions with a mean RIO of 11. The paper suggests that this means that ice drifting may have existed. Indeed, the vessel collided with drifting ice that seriously impacted the hull and the propeller shaft. The vessel could not sail for the next two months because of the damages to be fixed at a shipyard. There were also examples where a vessel could not sail through when the RIO value was positive, and the vessel had to wait for an icebreaker to be escorted. This study emphasized the importance of the officers' skills and experience to assess situations properly and the capacity of their vessels to sail in risky areas. Sailing in apparent safe areas in terms of positive RIO does not mean that there is no danger, as the cases in this study pointed out. This study is the only one the author has found that calculates the RIO vessels transitting the NSR.

There is also one publication about using POLARIS in the northwest passage that's of extra interest. This publication focuses on route evaluation with historical and near real-time data (5). The study helps identify areas along a route where a vessel can have sea ice or glacier ice problems. IA vessels are used for most planning and evaluation calculations in the study, but some focus is on operations whit a PC6 vessel. The main takeaway from this study is how a POLARIS can be used to predict operability based on historical data. The results a presented as risk maps and can be used to understand how ice may influence a particular vessel's behavior along a route. The study is limited to one route in the NWP and is not considering a transit route. However, the method used is relevant for this thises.

Related work within the area of POLARIS in the arctic was investigated to determine to what extent existing literature or research had already answered the proposed research question. Most of the related work focused focusing smaller areas, smaller datasets, accidents, and higher ice classes. The few related studies that considered POLARIS a risk tool for vessels were limited to smaller areas such as the Kara Sea, Svalbard, and Greenland. The studies were often considered higher ice classes, usually class A vessels, and were considering the past without trying to predict the future. However, one study was found on the Northwest Passage. This study used POLARIS as a planning tool to predict the operability of a short voyage around Baffin Island. The study did not consider the NSR, vessels with lower ice classes, or historical risk analyses based on POLARIS. Since the existing literature did not fully answer the research questions, this thesis goal was to develop a model and method capable of using historical data to predict the risk and operability of a vessel transiting the NSR. In collaboration with DNV it was advised to focus on vessels with lower ice-class because the hull shape of these vessels is more effective in open water, resulting in a more versatile cargo vessel.

2.0 Background

2.1 Northern Sea Route

The northern sea route (NSR) is the shipping route running along the Russian coast. The entire route is in the arctic region and the exclusive economic zone of Russia. The route is defined from the Bering strait, along the Siberian coast, to the Kara Sea. Adolf Erik Nordenskiöld leading the Vega expedition, was the first expedition to sail through the NSR in 1879. The Vega expedition was also the first successful arctic expedition through one of the Northern passages and opened a new and shorter route.

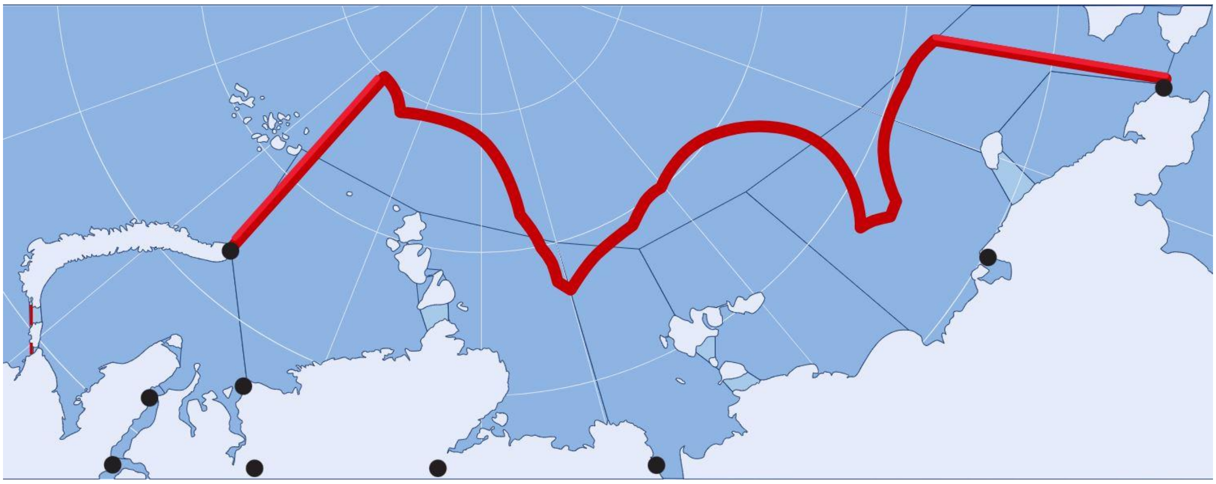


Figure 1: The Northern Sea route borders are marked with red (6)

There are different reasons to use the NSR, and one of the most important is geopolitical advantages. Today 80% of the industrial production and 70% of the cities with over 1 million are located north of 25 degrees north. Shipping gods between these places results in a distance advantage when vessels use the NSR compared with the Suez- or the Panama Canal. The advantages when vessel sails from Tromsø to Yokohama are vast. In this case, the usual route is thru the Suez Canal, resulting in a 12 400 nautical mile voyage. On the other hand, a voyage thru the Northern Sea route results in a 5600 nautical miles voyage and reduces the total distance by 55%. Another example can be a ship sailing from Tromsø to Vancouver. Sailing thru the NSR compared to the Panama Canal is a 37% reduction in the distance (7). The Russian scientist Mikhail Vasilyevich Lomonosov described the importance of the NSR as "the power of Russia shall be increased by Siberia and the Arctic Ocean." (7). At the same time, it can be argued that the NSR is less relevant as an international trading route due to the political uncertainties around Russia.

Today the west part of the NSR is most used, and most voyages are internal traffic. From table 1 there is also clear that it is a 200% increase over three years in transits through the NSR. The number of vessels sailing through is still tiny compared to the total voyages in the area, 0.4%-0.8% of the total (8). Today, international transit voyages are primarily exploratory and essential to demonstrate and evaluate commercial possibilities. The summer-autumn navigational season on the NSR is five months and extends from the beginning of July to the end of November, with the most activity in August and July. In the winter-spring season, less than 50 vessels were sailing through the NSR.

Departure and arrival destinations	2016	2017	2018	2019
From NSR to Russian ports	599	591	564	646
From western Russian ports to NSR	576	537	537	609
From eastern Russian ports to NSR	46	30	33	44
From NSR to European ports	78	62	144	287
From European ports to NSR	65	63	137	272
From NSR to NE Asian ports	15	4	4	21
From NE Asian ports to NSR	36	9	10	25
Transits via NSR (total)	18	28	27	37
Total number of voyages	1705	1908	2022	2694
Total number of different vessels	297	283	227	278
Total number of shipping companies	129	121	90	119
Total number of sailing permits (NSRA)	718	644	792	799

Table 1: Statistics NSR (9)

2.1.1 Weather

The arctic environment can be harsh with strong winds, polar lows, waves, reduced visibility, and low temperatures (10). These factors make it extra challenging to navigate vessels, and rapid changes make planning challenging. The weather also influences the analysis of the conditions, and specific satellite data can be challenging to use in different weather conditions. For example, waves can make it difficult to detect a vessel, and optical images taken in foggy conditions are useless. The climate changes through the NSR, and there are significant variations in terms of weather. Therefore, it is important to understand the effect of weather for both operational and planning purposes. The most relevant climatological factors for the NSR are listed on a broad basis under (10):

- **Wind:** The main problem with wind is that it can move ice fast, making the ice chart outdated when published, and the ice charts do not show the actual conditions when a voyage is planned. For example, a lead can open and close on short notice when the wind changes. When it comes to where the weather is most challenging in terms of wind, eastern parts typically have many storms in the winter months.
- **Polar lows:** Polar lows are small and short-lived low-pressure systems that are difficult to detect using conventional weather reports. They tend to form near the ice sheet or close to land and usually disappear after 1-2 days. However, their strong winds and heavy rain/ snow can be hazardous to vessels operating in the NSR.
- **Waves:** Waves in the NSR can be up to 4-5m and usually occur in the summer months when it is ice-free. When the NSR is covered by ice, waves are typically damped by the ice and are not a problem.
- **Fog/ reduced visibility:** Fog often covers large areas of the NSR and especially in the summer. Sea fog forms when a humid air mass crosses over colder ocean waters or cold air moves over warmer seawater. The result is saturated air with a relative humidity of 100% and poor visibility. Because this weather phenomenon is common for the NSR, there is just a couple of

days in a year where there are clear skies. Although combinations of snow and wind can also reduce visibility, this usually is only a problem in the winter and early spring.

- **Temperature:** The temperature in the west part can be up to 10 degrees in the summer and -30 degrees in the wintertime. The middle part of the NSR has a temperature just above 0 degrees from June- to September, and in the wintertime, the temperature falls to below -30. A graph of the average temperature around Dikson can is shown in figure 2.

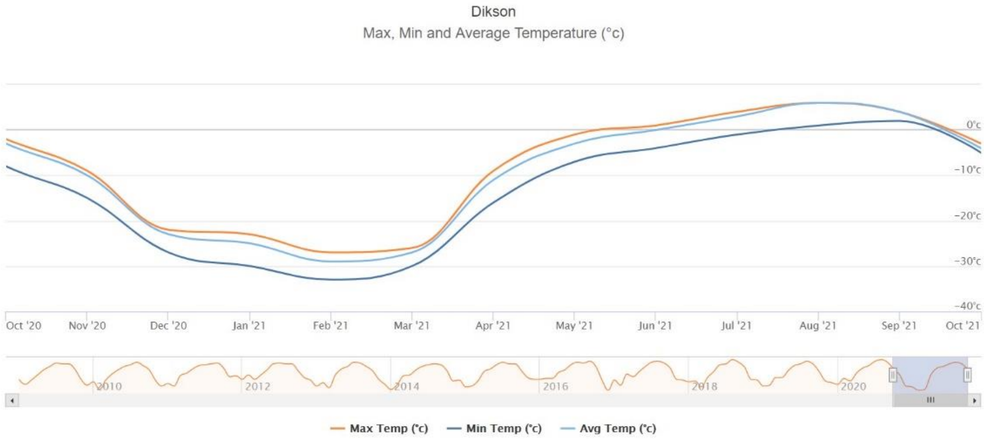


Figure 2: Average temprature Dikson int he NSR (11)

2.1.2 The future of NSR

NSR is not open for year-round shipping. In the winter months, Ob Bay and YeNICei River westwards via the Kara Sea are the only areas that can be easily accessed. Moreover, international shipping companies rarely consider the NSR a good alternative to the more conventional transit routes because of the limited time window. Therefore, there is a need for more research and operational experience if the NSR is considered a commercial trading route. However, Russia wants to make the NSR a year-round alternative. It plans to build five new nuclear icebreakers (three 60MW and two 120MW icebreakers) (8) to increase the operability of the route. The first icebreakers will be operational in 2028. Russia hopes to make the NSR a year-round shipping route within 8-10 years. The opening time of the NSR can be further reduced by increased climate changes or improved technology for icebreakers. There is also increased Russian government activity in building and planning infrastructure along the NSR. The new infrastructure is focused on Russia's interests in the area instead of servicing international vessels on transit voyages. Several experts have also pointed out challenges regarding difficult ice conditions in the eastern part of the NSR. The eastern part is challenging during the winter and spring months (10).

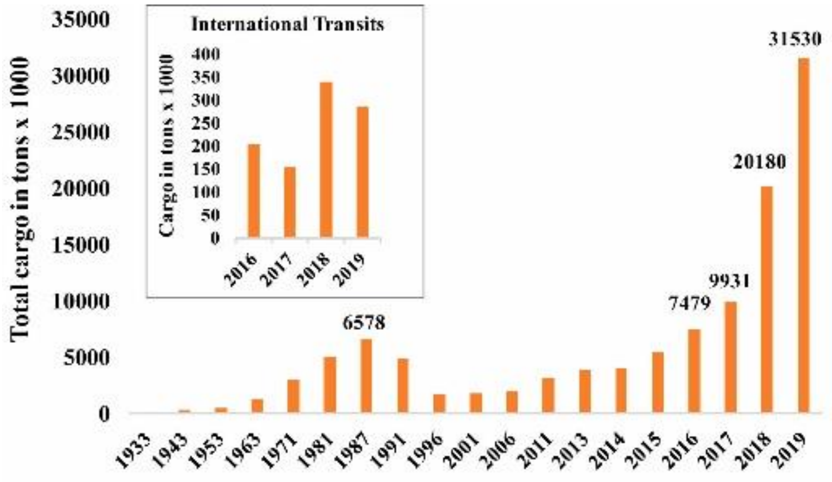


Figure 3 International transit in tons and cargo transited in tons (8)

Since 2006 there has been an increase in the total cargo tonnage transported through the NSR. The trend is clear, and it is expected that this will also continue in the future. Figure 3 shows a decrease in total cargo tonnage transported by international companies. Increased domestic shipping will also result from geological and geophysical exploration of Russian Arctic seas and coastal areas and in establishing, servicing, and maintaining current and future energy and mineral mining projects in the remote regions of the Russian Arctic. These projects include several planned LNG and gas condensate projects in the Ob Bay (8). The Russian government has established a plan to develop their arctic region further. However, the Russian Merchant Shipping Code only allows Russian flag vessels to transport hydrocarbons inside the NSR borders from 2018. The companies with contracts can still operate, but they will be phased out. There are also planned several transshipment and storage facilities for LNG on the Kola Peninsula near Murmansk and the Kamchatka Peninsula in the North Pacific in the east along the NSR. The new plants will secure an increased Russian control of future LNG projects and reduce the need for foreign companies. Putin has also stated that "Russia will strive to become the world's largest LNG producer" (8). Therefore, domestic transportation in the NSR will likely increase in the following years.

2.2 The Northern Sea Route AdmiNICtration

The Federal state Institution Northern Sea Route AdmiNICtration (NSRA) is a part of the Russian federal agency for maritime and river transport and the Russian MiNICtry of transport. The main targets of the Institution are ensuring safe navigation and protection of the marine environment from pollution in the area of the Northern sea route. (6) Today, the NSRA handles permissions to sail in the NSR and is an important open-source database where all applications from 2013 to today are published. The application includes vessel information, IMO number, and Ice-class essential for an RIO model.

The NSRA decide if a vessel is allowed to enter the NSR or not, and they also enforce the rules for when NSR is open for a given ice class. The updated rules for the NSR were adopted in September 2020, and they are stricter than the old rules for lower ice classes transiting the NSR (12). Since the old rules are easier to use in a go/ no go approach and there is more experience from using them, DNV advised using them to validate the final model. Table 2 sow an example of vessels with lower ice class. The old rules for ships without ice strengthening and ice strengthening Ice1 to Ice3, navigation in the NSR from November 16 to December 31 and from January to June is prohibited. However, vessels without ice strengthening can navigate the NSR independently only in open water (10). The period when the NSR is ice-free will warry from year to year. However, the duration of the navigational season for transits is greatly affected by the date when the Vilkitsky Strait in the archipelago Severnaya Zemlya becomes blocked by the systematically growing ice cover. Figure 4 shows the dates when this statically occurs according to American Bureau of Shipping.

Minimal relative area of ice cover (%)	Air temperature (°C)	Type of time of freezing of the region	Approximate date of beginning of the NSR freezing	Approximate date of occurrence of *young ice* at Vilkitsky Strait
27	−0.7	Late	21–30 Sept	01–05 Oct
38	−1.4	Average	11–20 Sept	~30 Sept
72	−3.0	Early	01–10 Sept	~15 Sept
85	−3.7	Extreme early	21–31 Aug	10–20 Sept

Figure 4: Information about the beginning of the NSR region freezing from the minimal relative ice-covered surface. Temperature and dates for when it freezes. (10)

Ship's ice reinforcement class	Ice navigation mode	The Kara Sea		The Laptev Sea		The East Siberian Sea		The Chukchi Sea
		Southwest part	Northeast part	Southwest part	Northeast part	Southwest part	Northeast part	
		H M L	H M L	H M L	H M L	H M L	H M L	
No[2]	Ind.[3]	- - -	- - -	- - -	- - -	- - -	- - -	- - -
	IA	- - +	- - +	- - +	- - +	- - +	- - +	- - +
Ice1	Ind.	- - +	- - +	- - +	- - +	- - +	- - +	- - +
	IA	- - +	- - +	- - +	- - +	- - +	- - +	- - +
Ice2	Ind.	- - +	- - +	- - +	- - +	- - +	- - +	- - +
	IA	- + +	- + +	- - +	- - +	- - +	- - +	- - +
Ice3	Ind.	- - +	- - +	- - +	- - +	- - +	- - +	- - +
	IA	+ + +	+ + +	- - +	- - +	- - +	- - +	- + +

Table 2: For ships without ice strengthening meeting the criteria for categories Ice1 to Ice 3 during the navigation period from (10)

2.3 Polaris

The Polar Operational Limit Assessment Risk Indexing System (POLARIS) is the name given to a risk assessment approach for evaluating ice conditions and setting limitations for ships assigned an ice-class, or ships with no ice-class operating in Polar waters. Polaris provides a framework for a decision support system for planning purposes and real-time decision making, which can be used by the admiNICtration and masters to identify limitations and to ensure the guidance suitably aligns with the content of the polar ship certificate (2) . The POLARIS system has been developed based on experience from Canada (AIRRS system), Denmark and Finland/ Sweden (Baltic FSICR class), and Russia (RMRS and NSRA). The first draft of the Polar Code assumed 100% ice coverage of one ice type, but in the real world, a 100% ice coverage of one ice type is very rarely met (13). The international maritime organization which made the International Code for Ships Operating in Polar Waters, also called Polar Code, does not state in the polar code from 2014 that Polaris can or should be used. Instead, it was advised to use it in the IMO guidance from 2016.

Today POLARIS and the Canadian AIRRS system are commonly used to determine risk for vessels operating in areas with sea ice. Regarding the significant difference between POLARIS and AIRSS, POLARIS allows for the consideration of limited speed and escort operations and the effects of seasonal ice decay. The addition of limited speed operations was included in POLARIS after input from operators in the Arctic. When operating in the artic, the vessel usually met difficult conditions they could operate in with due caution, although this is above the nominal limits given by AIRSS (2)

2.3.1 Development of Polaris

To gain a broader understanding of POLARIS the development and methodology are discussed in further detail. The development was conducted based on the existing content in the IMO Polar Code, and is illustrated in figure 5. In addition, the Polar code worked as a guide and reference to set limitations for the new methodology, together with experience from regional and national systems. Thus, POLARIS was developed based on a broad experience from a working group of delegations from Finland, Canada, Russia, and IACS.

From Polar code studies, three key elements were determined to identify and understand the ice conditions. Ice is complex, and instead of looking at ice as a single level ice condition, the three following factors were studied in detail:

- Ice concentration – Adjust the limitations for level ice for partial concentrations.
- Summer/ winter conditions – Adjustment because of decayed ice
- If a vessel is escorted or not.

Two additional main elements were added to have a systematic approach:

- Initial validation of the level ice thickness limitations
- Align the limitations for level ice with the WMO Egg Code descriptions as far as possible

These five key elements were the building blocks in developing POLARIS and will be discussed further.

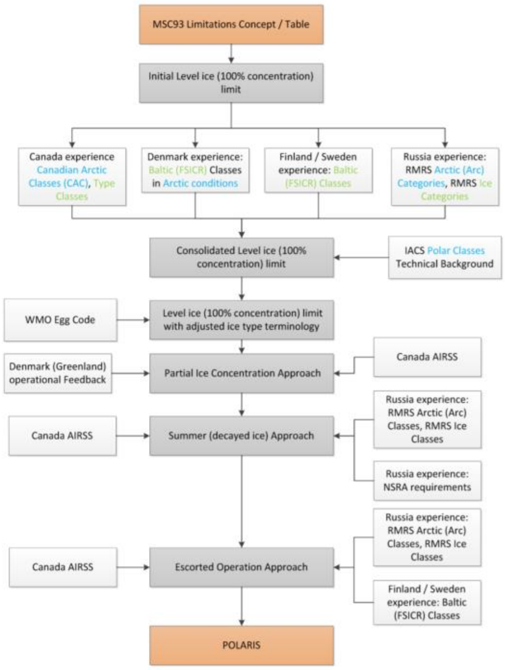


Figure 5: Process for developing POLARIS (2)

As seen in figure 4, different countries have determined an approach that can use different conditions worldwide. For example, the Transport Canada Arctic Ice Regime Shipping System (AIRSS) is a vital risk indexing system like Polaris. When Polaris was developed, AIRSS was the most readily available tool to evaluate different partial ice conditions. Figure 4 shows how the AIRSS system has been important input in developing POLARIS in different parts o the process.

2.3.2 Ice thickness limitations

The ice thickness limitations in POLARIS was undertaken using experience from the operation of open water and ships of ice classes from the Russian Arctic, the Canadian Arctic, Gulf of St. Lawrence, off the Greenland coast, in the Baltic, and the design and background to the IACS Polar Class Rules. The data of how ships of various ice classes are treated with respect to ice conditions under their various traffic systems are visualized in Figure 6. There is a broad agreement regarding the limitations for when a vessel can operate. However, these limitations are based on 100 conentration and a methode to determien the limitations for partial concentrations had to be developed.

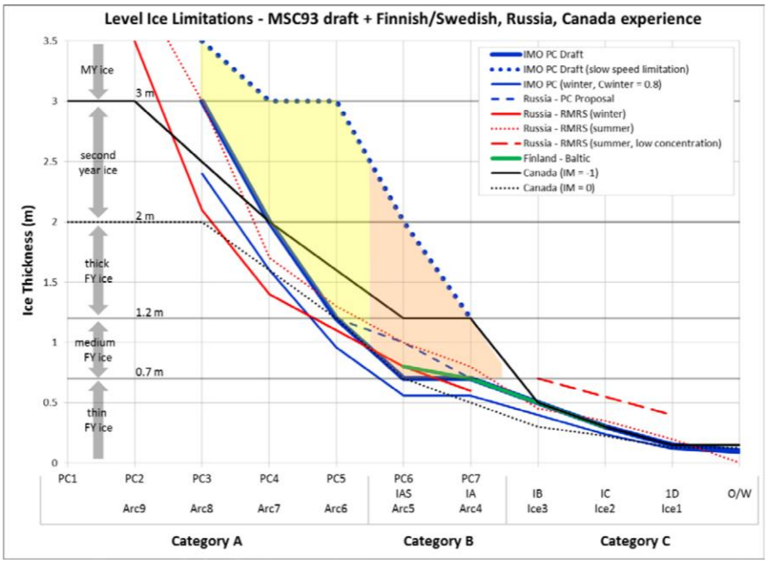


Figure 6: Limitations for level ice – MSC93 draft with operational experience from Canada, Finland/Sweden and Russia (2)

2.3.3 Ice concentration

Earlier approaches largely used 100% ice concentration of level ice to determine the operational limitations. However, one ice type is very rarely encountered in ice regimes globally but is a combination of various types of ice. It is also the method used in the WMO Egg code, where an ice chart divides the total concentration into partial concentrations. Thus, the characteristics are described as partial concentration for each floe size and stage of development. The approach for partial ice concentration is based on the AIRSS system, where each ice type is assigned a relative score that reflects the risk. Then, each partial concentration in the regime is multiplied by the proportion in % of that ice in the regime. As seen in Figure 5, experience regarding the operation in partial ice concentration from Denmark (Grenland) was also considered when this approach was developed.

2.3.4 Decayed ice

Sea ice is weaker in the summertime, and the risk of damage when the ice has begun to warm during the summer is reduced. When ice is warmed, it is called decay, and the softer ice makes it necessary to adjust the risk index in POLARIS. For the NSR, the summer season is from July to November. The Russian regulations implicitly consider this by addressing decayed ice's influence and allowing the operator to adjust the ice multipliers. The Canadian regulations (AIRSS) consider this explicit in their regulations (2). Therefore, these two risk indices are used in POLARIS, one for winter and one for summer. However, the approach has been that, where there is any doubt in identifying decayed ice, the Risk Index for winter should be used because this is a worst-case scenario (2).

2.3.5 Escorted operations

Operations with an icebreaker change the risk profile of the escorted vessel. Two different approaches were considered: AIRSS recommended evaluating the icebreaker track separately. The approach proposed by Finland was to adjust the RIO with a specific value. The last option was best for planning purposes, and it was considered to add a correction factor of +10 to the RIO. If the track of the icebreaker is narrower than the beam of the escorted vessel, the escorted vessel should evaluate its RIO based on the track (2). The icebreaker undertaking the escort should evaluate its RIO based on the ice regime and the ice class.

2.3.6 Align with EGG Codes

The ice charts for the Arctic and Antarctic consider a standardized terminology following EGG codes from WMO. This system is discussed in further detail in subsection 2.6.1. For the limitation system discussed above to work in practice, the limitations must be, as far as possible, consistent with those from WMO. However, the International Working Group on Ice Charting decided to subdivide two ice type definitions to produce a graded system that reflects the gradual increase in risk for the stages of ice development. The WMO definition of medium first-year ice is 70cm to 120cm. To reduce the large range and the risk related to it, IMO decided to subdivide it into Medium first-year ice and medium first-year ice second stage. The same was done for Light Multi-Year Ice and heavy Multi-Year Ice.

2.3.7 Methodology and risk calculation

The RIO is determined by a summation of the Risk index values (RIVs) for each ice type present in the ice regime multiplied by its concentration. The primary purpose of the RIVs is to assign a risk to a ship based on its ice strengthening and the development of ice in the area. Ice types generally conform to WMO EGG codes, ass discussed earlier. Table 7 shows the RIVs for winter operations.

Ice Class	Ice-Free	New Ice	Grey Ice	Grey White Ice	Thin First Year ice 1st Stage	Thin First Year Ice 2nd Stage	Medium First Year Ice less than 1 m thick	Medium First Year Ice	Thick First Year Ice	Second Year Ice	Light Multi Year Ice, less than 2.5 m thick	Heavy Multi Year Ice
PC1	3	3	3	3	2	2	2	2	2	2	1	1
PC2	3	3	3	3	2	2	2	2	2	1	1	0
PC3	3	3	3	3	2	2	2	2	2	1	0	-1
PC4	3	3	3	3	2	2	2	2	1	0	-1	-2
PC5	3	3	3	3	2	2	1	1	0	-1	-2	-2
PC6	3	2	2	2	2	1	1	0	-1	-2	-3	-3
PC7	3	2	2	2	1	1	0	-1	-2	-3	-3	-3
IA Super	3	2	2	2	2	1	0	-1	-2	-3	-4	-4
IA	3	2	2	2	1	0	-1	-2	-3	-4	-5	-5
IB	3	2	2	1	0	-1	-2	-3	-4	-5	-6	-6
IC	3	2	1	0	-1	-2	-3	-4	-5	-6	-7	-8
Not Ice Strengthened	3	1	0	-1	-2	-3	-4	-5	-6	-7	-8	-8

Figure 7: RVs for each ice type in the ice regime and the ice class. (14)

POLARIS uses a Risk Index Outcome (RIO), which is calculated by combining RVs for each ice type in the ice regime, multiplying it by its concentration in tenths, and summarizing it. Equation 1 is used to calculate the RIO. However, some exceptions to the calculation of RIO exist, and they are commented on in subsection 2.3.9.

$$RIO = C_1 * RV_1 + C_2 * RV_2 + C_3 * RV_3 \dots \dots + C_n * RV_n$$

Equation 1: POLARIS RIO

C_n = is the concentration in "tenths" for the given ice types within the ice regime. C also includes open water. The notation C is the same as used in the egg code. The summation of all values of C is always equal to 10. Thus the total concentration is 100 %.

RV_n = are risk index values corresponding to the ice-class and the season. For example, the risk index values for the winter season can be seen in figure 5.

2.3.8 Risk Evaluation and operational limit POLARIS

Operational limitations are determined from the calculated RIO and the ice class. IMO also states that factors such as weather changes and visibility should be considered. POLARIS addresses three levels of operation from the RIO:

- Operation Permitted
- Limited Speed Operation Permitted (see table 3)
- Operation not Permitted

Table 3 shows the RIO value and the corresponding operational limit. Vessels operating in an elevated risk ice regime should limit their speed. If the speed reduction impairs the vessel maneuverability, the operation should ve avoided. IMO has also opened up for adjustment if the vessel is equipped with ice load measurement and monitoring systems or if the vessel has undergone full-scale ice trials.

RIOvessel	**PC1-PC7**	**<PC 7**
RIO ≥ 0	Operation Permitted	Operation Permitted
-10 RIO 0	Limited Speed Operation Permitted (se table 3)	Operation not Permitted
RIO <-10	Operation not Permitted	Operation not Permitted

Table 3: Risk Index Outcome Criteria (14)

Limited speed for the different ice classes:

Ship Category (ice class)	**Independent operation**
PC1	11 knots
PC2	8 Knots
PC3-PC5	5 Knots
PC7	3 Knots
< PC7	-

Table 4: Recommended speed limits for elevated risk operations (14)

2.3.9 Operations Subject to Ice Decay, glacial ice and icebreaker escort

There are three types of operations where the RIO calculations should be adjusted. This is if the ice regime consists of ice decay, if the ice regime contains glacier ice, or if the vessel is under icebreaker escort. In cases with ice decay, the RIV values are adjusted by adding a value of one to Medium and Thick First Year Ice for lower ice classes. For vessels operating in ice regimes containing glacier ice should appropriate training be provided to the Master and officers. Measures to avoid glacial ice should be documented in the PWOM. Finally, the ship should obtain a safe stand-off distance in addition to the RIO calculations.

For vessels under icebreaker escort, the ice regime defines as the ice between the vessel and the icebreaker. In this operation must the icebreaker evaluates its own risk and calculate an RIO along its intended route. When the icebreaker has a smaller beam than the escorted ship, any unmodified ice out to the maximum beam of the escorted ship must be included in the calculations. For planning purposes, non-escorted historical ice data may be assumed to be modified by adding 10 to its calculated value. For actual operations, should the RIO be calculated for the actual ice regime ahead of the vessel.

2.4 Ice classes

Vessels have for centuries been strengthened to operate in sea ice, and the first official rule-based standard for ice classification was introduced in the 1930s by the FinNICh and Swedish authorities. Then the Soviet Union developed its own rules before Canada got their own rules in 1970. The DNV GL classification has divided vessels operating in sea ice into three parts. The first part is the classification of ships in the Baltic regions. This regulation was initially developed by the FinNICh-Swedish class societies and was later implemented in DNV GL. The second part is a standard ruleset for operations in ice-infested polar waters. The third and final part is for ships traveling in the Arctic regions. Ice classes is an important part of POLARIS, and it is essential to understand how the different regulations and conversions between them will affect the calculated risk picture.

Today Russia, Sweden/ Finland, and IACS have rules and definitions for determining the ice classes. The different standards make it difficult to directly convert or compare different ice classes. For example, the Canadian rules are based on linking ice loads to physical parameters, and the Swedish/ FinNICh, on the other hand, consider that an icebreaker can assist a vessel when it operates. Lastly, the Russian rules are based on a different model that has not been described in the open literature (2). There is no explicit modeling between the parameters in the different regulations, making it challenging to compare ice classes. The following sections describe the most relevant ice-class operations regulations in the NSR.

2.4.1 IACS Polar Rules

The international association of classification societies (IACS) has developed a set of polar rules for all ships constructed of steel and intended to operate in ice-covered polar waters. Except for the Russian Register, all classification societies have adopted the IACS ice classes, the standard used in POLARIS. The IACS rules determine the ice-class from structural strength and machinery. The ice classes used in POLARIS can be described based on the WMO sea-ice nomenclature, as seen in Table 5. The International Association of Classification Societies (IACS) has also published "Unified Requirements for Polar Class Ships" to complement IMO Guidelines for vessels operating in ice-covered waters. The rules and regulations are referred to in the IACS UR sub-section Polar Class (PC) (15) , and as mentioned, this is a general description of ice classes. It is still possible to damage the ship by careless operations within the limitations.

Polar Class	Ice description (based on WMO sea ice nomenclature)
PC 1	Year-round operation in all polar waters.
PC 2	Year-round operation in moderate multi-year ice conditions.
PC 3	Year-round operation in second-year ice which may include multi-year ice inclusions.
PC 4	Year-round operation in thick first-year ice which may include old ice inclusions.

PC 5	Year-round operation in medium first-year ice which may include old ice inclusions.
PC 6	Summer/autumn operation in medium first-year ice may include old ice inclusion.
PC 7	Summer/autumn operation in thin first-year ice, which may include old ice inclusions.

Table 5: Polar classes with ice description (based on WMO sea-ice nomenclature) (15)

The different regulations make it difficult to convert or compare the Russian ice classes to the IMO Polar code used in Polaris. IMO made a graph comparing the different ice classes, and as seen in figure 6, there is a broad agreement between the systems. However, when studying other sources, it is clear that there are different standards for converting the ice classes. Table 6 shows converting tables for IACS Polar rules to Russsian ice-class rules.

PC1	PC2	PC3	PC4	PC5	PC6	PC7	Source	Ref
	Arc9	Arc8	Arc7	Arc6	Arc5	Arc4	Polaris and IMO 2014	(2)
	Arc9/ Arc8	Arc7	Arc6	Arc6	Arc5	Arc4	IMO 2010	(16)
Arc9	Arc8	Arc7	Arc6	Arc6	Arc5	Arc4	Publication	(12)
	Arc9/ Arc8	Arc8	Arc7	Arc6	Arc5	Arc4	Chugoku Marine Paints	(17)
Arc9	Arc8	Arc7	Arc6	Arc5	Arc5	Arc4	Bureau Veritas	(18)

Table 6: Converting Russian ice classes to IACS Polar Rules

2.4.2 FinNICh-Swedish Ice-class

The FinNICh and Swedish authorities have developed the FinNICh-Swedish Ice-class Rules (FSICR) based on accumulated experience and extensive research. This standard is mainly used for first-year ice, and all classifications societies, apart from IACS and the Russian register, have adopted these classifications as their first-year ice rules. Therefore, DNV GL ice classes can be accepted as equivalent to the FinNICh-Swedish ice classes. The different ice classes set minimum requirements for engine power and ice strengthening. Minimum engine power is required to ensure the smooth progress of traffic in ice conditions and is determined for vessels sailing in brash ice. An ice breaker can assist a vessel operating in the Baltic region, and the ice classes assume that icebreaker assistance is available when required. Therefore, vessels designed for independent navigation in areas other than the Baltic Sea should account for this.

The equivalence of the lower ice classes of the Russian Classification Societies and the FinNICh-Swedish Ice-class rules can be converted based on different sources. Table 7 is converting tables from various sources listed. The Baltic Marine Environment Protection Commission (BMEPC) has suggested the equivalent ice classes based on structural hull requirements. Equivalence is estimated because the hull structural strength given by the rules of a classification society is similar to the hull structural strength obtained by applying the FinNICh-Swedish Ice-class rules (19). IMO/ POLARIS has changed the equivalence for Category II because Finland noted that the designation Ice-class, as used in the FSICR was: “Ships that have a steel hull and that are structurally fit for navigation in the open sea and that, despite not being strengthened for navigation in ice, are capable of navigating in very light ice conditions with their propulsion machinery.” (2)

IA Super	IA	IB	IC	Category II	Source	Ref
Arc5	Arc4	Ice 3	Ice 2	Ice 1	Baltic Marine Environment Protection Commission	(19)
Arc5	Arc4	Ice 3	Ice 2	No Ice class	Polaris and IMO 2014	(2)

Table 7: FinNICh-Swedish Ice-class Rules (FSICR)

2.5 Satellites

Satellites are incredible instruments for studying the sea ice and monitoring vessels from AIS or radar signals. Satellite data may provide statistics on sea hydrological models, sea ice concentration, stage of development, and ice thickness (20). Due to the large and unavailable areas of the Arctic sea, the preferable monitoring approach is, in general, remote sensing with the use of satellites. Remote sensing is acquiring information about an object, area, or phenomenon from a distance (21). In recent decades, the field of sea ice monitoring by satellites has undergone drastic improvements, and today is radar and optical satellite sensors essential when investigating sea ice (22). Another aspect of satellite monitoring is the ability to make satellite information available to users in an understandable format shortly after it is recorded. The main advantage of satellite images compared to ice charts is the updating rate. Ice charts are published weekly for the NSR, but the satellite images are published more than once a day. Ice charts in the polar regions usually are manually drawn by experienced sea ice analysts.

An example where satellite images can be helpful is when an ice chart is made based on a satellite image taken the day before. After the satellite image was taken and before the ice chart was published, the weather and the wind increased, resulting in the wind pushing the sea ice North and a clear sailing path close to shore open. The captain then sees this opportunity and continues sailing through the passage. When the RIO is calculated from the outdated ice charts, will the risk be higher than the actual risk the captain had calculated/experienced from the bridge. However, a satellite image for the same day will be able to determine the lead. Therefore, satellite images are essential to get an updated risk picture and validate the ice conditions from the ice chart. This chapter contains the most relevant satellite types for determining the ice conditions and data collection for AIS data presented. For determining ice conditions, open-source data has been the main focus of this thesis.

2.5.1 Sentinel – 1 (SAR)

Sentinel – 1 is the satellite program commonly used for studying sea ice. The satellite is an initiative from the European Space Agency (ESA) and uses radar to sample data. One of the main advantages of using data from Sentinel-1 is the short revisit times and rapid product delivery (23). Currently, two different satellites are operating in the Sentinel – 1 program. Sentinel – 1 A launched in 2014, and Sentinel – 1 B was launched in 2016. The satellites have Synthetic Aperture Radar (SAR), which uses wavelengths not impeded by rain, clouds, or lack of illumination. The radar can collect data in all weather, day or night, and measurements at high and medium resolutions for land, coastal zones, and ice observations (23). NASA started studying artificial intelligence for sea ice classification using SAR images in 1990. The study ARKTOS was developed over ten years by NASA (24) and was one of the first fully automatic, near real-time artificial sea ice classification systems. The combination of short revisit time and the ability to collect data in all-weather makes these satellites suited for monitoring sea ice and vessel detection. For the Arctic region, the Sentinel – 1 visits the area every > 2 days. A higher resolution picture is taken every fourth day for the southern part.

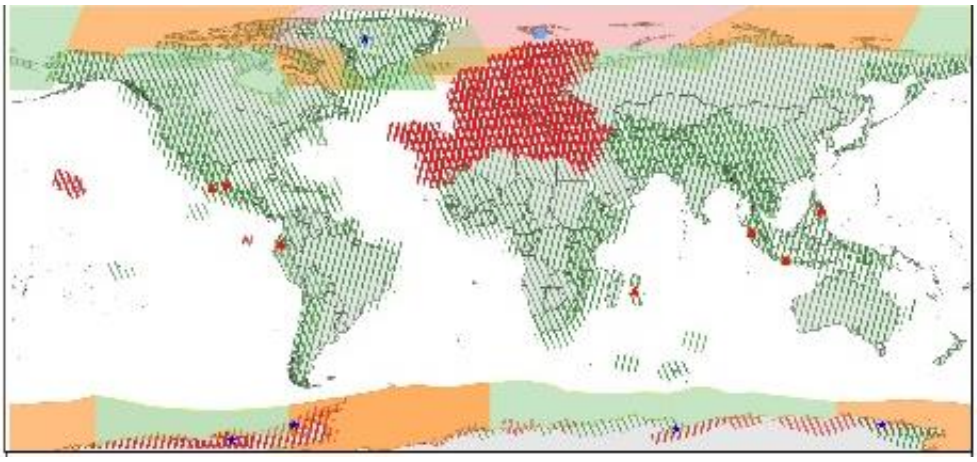


Figure 8: Sentinel-1 coverage and revisit time. Red is visited once a day with a lower resolution. Green is 2-4 days between visits, but the resolution is higher than the red area (HH). (23)

2.5.2 Synthetic Aperture Radar (SAR)

The Sentinel 1 satellite has a C-SAR instrument that operates at a center frequency of 5.405 GHz. The C-band radars operate within the microwave portion of the electromagnetic spectrum, resulting in an image of the top layers of the earth, but at the same time are not hindered by atmospheric noise. The C-SAR has three ways of collecting data: Stripmap (SM), Interferometric Wide swath (IW), Extra-Wide swath (EW), and Wave mode (WV). The EW is intended for maritime data collecting because it has a short revisit time and broader coverage. A broader coverage results in a lower resolution, and for EW mode, the resolution is 20m x 40m (23). On the other hand, IW can also be used but is more commonly used to collect land data.

An essential part of the SAR instrument is the SAR Antenna Subsystem (SAS), allowing for horizontal and vertical (H or V) polarization (25). Polarization is the process of receiving vertical or horizontal wavelengths by the antenna. The polarization is relative to the antenna co-ordinate system. The transmitted signal used in polar regions is horizontal waves which are backscattered as vertical (HV) or horizontal (HH) polarization. In the southern part of the NSR, is it possible to obtain VV and VH data. The VV and VH scan only visits 2-4 days but has a higher resolution than HH. The different polarization can detect different sea ice conditions or help separate a vessel from its surroundings. Therefore, it is essential to understand what objects reflect specific signals in the different polarization channels. For example, sea ice reflects most HH signals, but a ship reflects HH and HV. This knowledge can be used to visualize the different channels as an RGB picture.

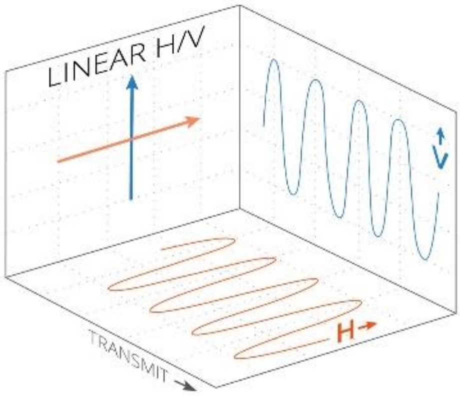


Figure 9: Polarization HH (Blue) and HV (orange) (26)

2.5.3 Sentinel - 2

SENTINEL-2 is a European wide-swath, high-resolution, multispectral imaging mission. The satellite has a revisit frequency of 5 days at the equator and is equipped with optical sensors. Optical sensors give images as we see them in real life. The satellite is equipped with a multispectral instrument. This sensor allows it to collect VNIR wavelengths and the three SWIR wavelengths. SWIR wavelengths are wavelengths on the infrared specter and are often used in the false-color picture. Here one of the color channels is based on SWIR wavelengths. The VNIR wavelengths are visible light and red/infrared light. This wavelength can make an image the way we see it. The disadvantage with the Sentinel-2 satellites is that they need clear skies to show the ice conditions or to be able to detect a vessel. Another disadvantage is that the ice conditions change rapidly and five day revisited time is not optimal. However, the long revisit time can be compensated by using the American satellite program Landsat, another open-source satellite with similar sensors. Therefore, the satellites from Landsat can make the same image, but the overall revisiting time is reduced when the two programs are combined. This satellite image can be suitable supplementary if the image is taken on a clear day. However, as discussed in subsection 2.1.1, the NSR is known for fog and skies, making optical imaging less relevant and only an additional data source for ice mapping and vessel detection.

2.5.4 Determine the condition of sea ice

The detecting, tracking, and prediction of sea ice are significant for vessel navigating, marine activities, and the surveillance of sea-ice mechaNICms and patterns. This review highlights the latest satellite-based detection improvements relevant to sea-ice analyses. Sea-ice conditions and extremes must be detected, monitored, and forecasted on a short and seasonal time scale. In the most basic scenario, non-ice-class vessels merely need real-time observation and predictions of sea-ice edge location. At the same time, tactical navigation of ice-strengthened vessels requires precise information such as localized sea-ice thickness variations.

Furthermore, vessels are often built to withstand the stresses caused by static pack ice but not to withstand severe sea-ice conditions. As a result, observations of the thickest and heavy multiyear ice types, pressure ridges, thick windrow/brash ice layers, and icebergs are of extra interest to operate safely in these areas. In addition, glacier icebergs are considered the strongest ice types off the extremes. Consequently, these have become essential monitoring metrics for risk management in ice-covered seas. Operations in ice regimes with glacier ice are also something POLAIRS has highlighted as extra challenging with increased risk. Therefore, accurate monitoring of glacier ice is extra important around the Vilkitsky Strait, where this problem often occurs.

Another sea-ice monitoring program is the Space-borne Observations for Detecting and Forecasting Sea-Ice Cover Extremes (SPICES) program. The SPICEs program is funded by the EU's Horizon 2020 program SPICES has generated new sea-ice deliverables based on a broad range of Earth Observation data from several satellite observations and numerical meteorology modeling (27). This study utilized a range of in-site ice and sea-ice information combined with aerial remote-sensing data to construct and validate sea-ice products. These products include ice thickness, melt pond detections, and degree of ice ridging based on synthetic aperture radar imagery (28). The SPICES have shown how Soil Moisture and Ocean Salinity (SOMOS), combined with SAR sensors, have resulted in better forecasts of July sea-ice conditions. This period is when it is the most challenging time for the SAR to retrievals of sea-ice parameters as they are affected by the liquid water on the sea-ice surface (28). It is the SOMOS data that has helped determine thinner ice. Various sources have stated that with a reasonable amount of further work, new models can be integrated into various commercial and operational sea-ice services, resulting in better forecasting of sea ice and ice charts. (29) (30) (31).

2.5.5 Visualizing ice conditions with Sentinel-1

Sentinel 1 A and B SAR-C data are the most important sources of information for functional ice mapping (27). When analyzing sea ice, it is most common to use EW and only one type of polarization. However, an image combining the two polarizations HV and HH, typically results in a more detailed picture of the sea ice. When making an RGB image, the different HV and HH wavelengths are assigned to a color (red, green, or blue) to visualize the sea ice characteristics. A method developed to do this is the "SAR-Ice: a sea ice RGB composite" developed by Raspaud and Itkin (32). This method uses the advantages of cross-polarization to visualize the conditions better.

The cross-polarization can be combined to visualize different sea ice conditions by combining HH and HV. Typically HH polarization is the most common backscatter when monitoring sea ice, and this is also the strongest signal compared to HV signals. HH polarization is sensitive to reflect signals from flat surfaces and has advantages for visualizing sea ice and the ocean. On the other hand, HV polarization is more sensitive to snow and ice because of more air bubbles. For example, first-year ice appears different from multi-year ice because of the air bubbles and salinity difference. In addition, HH and HV cannot visualize dry snow and often have problems visualizing the ice type in the summer months due to meltwater on top of the sea ice (33). Combining HH and HV signals, figure 8 shows how the following futures are visualized:

- Calm ocean water or wind roughened ocean surface

- Flat ice or rough ice
- First-year or multi-year ice
- Polynyas and leads

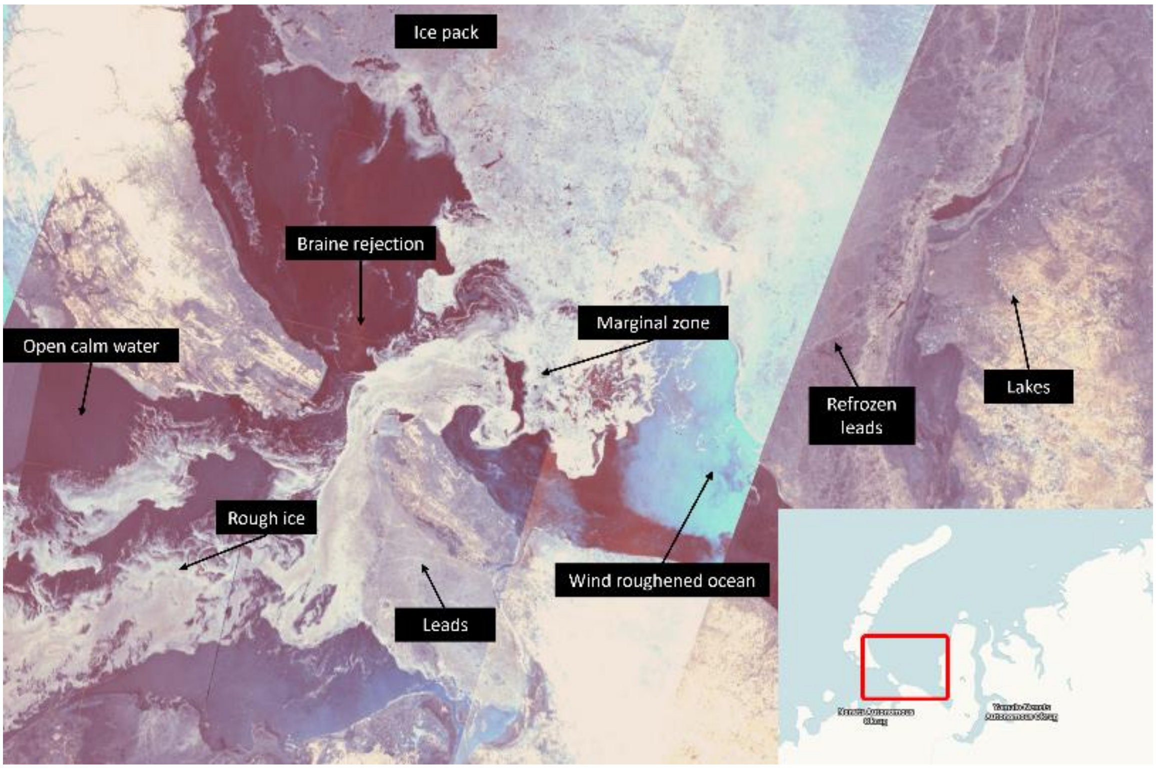


Figure 10: SAR image of different ice types from the NSR

2.5.6 Detecting vessels with satellite images

Vessel detection has been essential for maritime domain awareness. Maritime domain awareness has been defined as the practical understanding of any activity associated with the maritime domain that could impact the security, safety, economy, or environment (34). Detection of vessels from satellite images uses different sensors and can be divided into four main categories:

- Optical and reflected infrared
- Hyperspectral
- Thermal infrared
- Radar

2.5.7 SAR (Synthetic Aperture Radar)

Today, SAR is the leading theology for vessel detection, and Sentinel-1 is often used. As mentioned earlier, the main advantage of SAR is that it works at night or with a cloud cover. In addition, most vessels are made of metal. Their structure contains sharp edges that reflect radar signals intensively, resulting in the vessels on open waters coming across as bright dots and edges (35) (36)The operator trying to detect a vessel can then detect vessels by thresholding bright pixels in a cluttered background. It is also possible to take advantage of cross-polarization to highlight different phenomena. A disadvantage of thresholding is the difficulty of recognizing whether a white dot is a vessel, noise, high seas, ice, or other objects. This problem is especially a challenge in the arctic region, where the resolution of the picture is combined with sea ice and noise.

2.5.8 Optical images

Optical images are easier to analyze for untrained people because they work like the human eye. However, the optical images can be challenging to analyze if the presence of environmental noise in the form of cloud coverage, sunglint (sun reflected from the ocean), or weaves are present (37). However, different methods can be applied to minimize these factors. When it comes to analyzing the picture, different methods can be applied. The classical method of splitting the picture and then looking at the contrast or change in pixels is often used. However, machine learning or shape and texture-based algorithms are more complex methods.

The optical images usually are either true-color images or false-color images. A true-color image represents the colors the way our eye sees it. On the other hand, a false-color image combines at least one non-visible wavelength with the actual colors. The one channel making it a false-color can often be near the infrared spectrum. When a false color is used, the sea is often visualized as an intense blue or black color. It is also easier to get more information about the borders of an iceberg or the ice edge.

2.5.9 Comparison of detecting methods

The different methods have different strengths and weaknesses, and other methods not mentioned here can be applied. There is also a variety from area to area regarding how easy it is to detect vessels. In general, it is more challenging to detect ships in the arctic than in the area closer to the equator because of the different resolutions of the images. An example of this is shown in figure 9 for the arctic region and Kattegat

Comparrison of different vessel detecting methodes

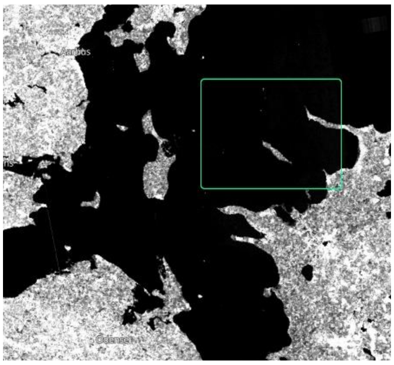
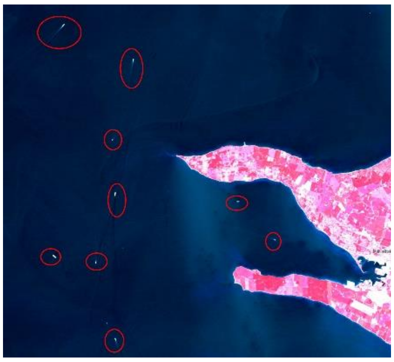
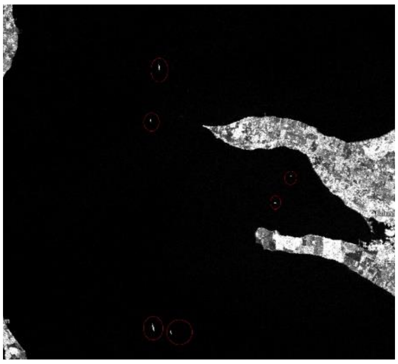
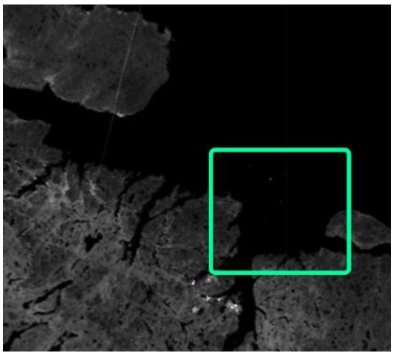
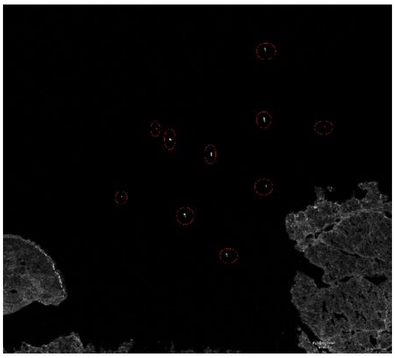
Overview map	Optical false-color zoomed in	SAR zoomed in
		
The area east of Samsø, Denmark	In this picture, multiple vessels can be seen, and the waves from the ship are also easy to see in calm water	The vessels can be seen as small white dots. The SAR image from this area has a higher resolution compared to the arctic regions
		
The area outside Murmansk	Two vessels can be seen. In the arctic regions, it is often challenging to detect the waves behind the vessels	This picture was taken in September with no ice. Then the vessels are easy to spot, and there is little difference between HH and VV pictures when it comes to detecting vessels. However, in conditions where there is a lot of sea ice, it is difficult to see a vessel or iceberg.

Figure 11: Vessel detection in the arctic region and Kattegat

2.6 Ice charts

Ice chars are maps characterized by contour lines to connect ice regimes. They are often manually drawn and are published regularly. Today, ice charts are one of the best ways to display the ice conditions in an area. Five northern countries monitor and provide ice charts Russia, Canada, Denmark, USA, and Norway for the Arctic region. These countries have different focuses on what data they represent in their ice chart. For example, the Norwegian ice charts only display the concentration. On the other hand, the Russian charts include the stage of development. The different countries also have different areas they deliver ice charts over. For example, Norway and Russia are most relevant for the NSR, but the US National Ice Center (NIC) makes ice charts covering the entire Arctic Ocean. However, the Arctic and Antarctic Research Institute (AARI) in Russia produces ice charts for the European and American parts of the Arctic. In the summer period (June to September), AARI ice charts contain information only on sea ice concentration and land-fast ice extent, while in winter (October to May), the data on stages of sea ice development is also presented. (38) The data can either be represented as PDF, JPG, or tabular form. Sea Ice Grid (SIGRID) format is the official tabular form for ice charts.

The national providers of ice charts use experienced sea ice analysts to study the SAR images and manually draw the ice charts from this analysis. Even though these analysts are efficient, manual ice charting is time-consuming and extends the waiting time before they are accessible. Another challenge, despite the professional skills of the analysts, there will always exist an element of subjectivity in the manually made ice charts. For example, the European Union's Earth Observation Programme, Copernicus, found that 90-95% of the ice edges were the same when comparing two ice charts (36)Additionally, they found that up to 10% of the points can differ with values up to 20% in the comparison. Thus, the accuracy of a manually drawn ice chart is limited.

2.6.1 Egg code

The international system of sea ice symbols is a visual and easy standardized presentation of the primary data: concentrations, stages of development (age), and form (floe size) of ice in a simple oval form. This convention was developed by the World Meteorological Organization (WMO). Figure 12 shows the egg code. This way of visualization conforms to an international convention and shall be used to code all visual sea ice and lake ice observations without exception (39). The presented Egg Code is the international system for sea-ice symbols. Nevertheless, regional or national systems can have additional symbols. Adjustments can be provided if they do not overlap or contradict the international system (39). The Egg code is also used in the SIGRID-3 format with some adjustments. The main assets in the egg code are:

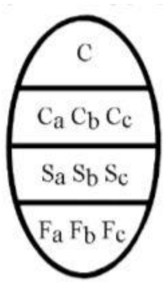


Figure 12: Egg Code (39)

- Total Concentration (C): Total concentration for the ice coverage is expressed in tenths.

- Concentration (C_a, C_b, C_c): Partial concentration of the highest concentrations (Ca), second of the highest concentrations (Cb), and third highest concentrations (Cc). All the numbers are in tenths. a, b, c is equal to a class of ice. This notation is also used for S, F and corresponds to the same ice.
- Stage of development (S): Stage of development describes the partial thickness.
- Floe size (F): Partial form of ice corresponding to the size of the floe. (40)

2.6.2 Detailing classes

Concentration

Ice coverage in an area is expressed by its total concertation in tenth. The ice coverage is divided into the following subclasses: ice-free, open water, very open drift, open drift, close pack/drift, very close pack, and compact/ consolidated. Figure 13 shows the different stages of concentration:

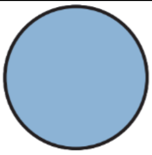
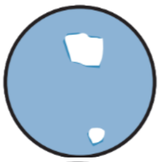
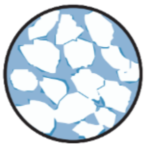
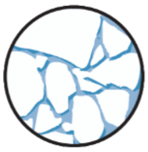
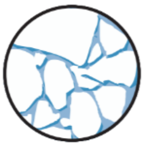
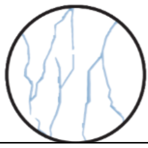
Ice coverage	Concentration	Sub class	Symbols
	No ice present	ice free	0
	1/10th	open water	1
	1/10 to 3/10^{ths}	very open drift	1-3
	4/10 to 6/10th	open drift	4-6
	7/10 to 8/10t^{hs}	close pack/drift	7-8
	9/10^{ths}	very close pack	9
	9+/10^{ths}	very close pack	9+
	10/10^{ths}	compact/consolidated ice	10

Figure 13: Ice concentrations in tenths (41)

Stage of Development (Ice Type)

The stage of development gives information about how thick the ice is. Hence, one of the most important factors in determining the risk in POLAIRS.

Stage of Development (Ice Type)	Thickness	Symbol
New Ice		1
Nilas; ice rind	< 10cm	2
Young Ice	10-30cm	3
Grey Ice	10-15cm	4
Grey-White Ice	15-30cm	5
First-Year Ice	30-200cm	6
Thin First-Year Ice	30-70cm	7
Thin FY, 1st stage	30-50cm	8
Thin FY, 2nd stage	50-70cm	9
Medium First-Year Ice	70-120cm	1 .
Thick First-Year Ice	>120 cm	4 .
Old Ice		7 .
Second Year Ice		8 .
Multi-Year Ice		9 .
Ice of land origin		Δ .
Undetermined or unknown		X

Table 8: Stage of Development (Ice Type) (41)

Type and size (Elements)

Elements are not used in POLARIS but are a part of the EGG code. Type and size give information about how big the ice is in the horizontal plane.

Element	Symbol
Pancake Ice	0
Small ice cake; brash ice	1
Ice Cake	2
Small Floe	3
Medium Floe	4
Big Floe	5
Vast Floe	6
Giant Floe	7
Fast ice, growlers or floebergs	8
Icebergs	9
Undetermined or unknown	x

Table 9: Elements (41)

2.6.3 Sigrid 3 – Digital ice charts

The Sea Ice Grid (SIGRID) format was developed in 1981 and formalized in 1989. Later, both Sigrid 2 and SIGRID 3 were developed. The SIGRID 2 format was on a **raster format,** where ice characteristics are represented on a grid. SIGRID 3 is a vector shape format that stores ice conditions, development, and concentration information. Using a vector format rather than a raster format has advantages. The vector file preserves all of the information in the original chart, and charts can be re-projected or rescaled without loss of information. SIGRID-3 has the advantage that all information is preserved in the vector format, compared to older methods using dot points.

The file consists of different attributes where the first part of the file shows the area and the perimeter. The next part in the file shows the total Concentration (CT). It is followed by partial concentrations of the first, second, and third highest concentrations (CA, CB, and CC) along with their respective stages of development (SA, SB, and SC) and form/ floe size (FA, FB, FC) (42). The variable is paired with a number representing a specific ice condition. Table 8 shows that the CT, CA, CB, and CC correspond to a given concentration. For example, 50 is equal to a 5/10 concentration, and 99 is undetermined. It is also possible to have a range for the concentration.

An example of this is 79 is equal to 7/10 – 9/10. The stage of development (SA, SB, and SC) has the same system with a number corresponding to a specific ice type. The values can be seen in Appendix C where for example, 83 corresponds to young ice 10-<30cm. The floe size (FA, FB, FC) follows the same system where a number corresponds to a concentration or size. If a mandatory ice field is not used, a dummy variable of -9 clarifies that the field is deliberately not used. The number 99 is used for undetermined/unknown values. This dummy and undetermined value can be used for all the above perimeters. The last part of the file displays the polytype, representing the surface types: land, water, ice, and shelf ice.

Ice concentration egg code format	SIGRID-3 code
Ice free	98
Less than 1/10 (open water)	01
Bergy Water	02
1/10	10
2/10	20
3/10	30
4/10	40
5/10	50
6/10	60
7/10	70
8/10	80
9/10	90
10/10	92
Unknown	99/-9

Table 10: SIGRID 3 to EGG codes

2.7 AIS

The Automatic Identification System (AIS) is an automated, autonomous tracking system that is mandatory to be fitted aboard all ships of 300+ gross tonnage engaged on international voyages, cargo ships of 500 or more gross tonnage not engaged on international voyages, and all passenger ships, irrespective of size. This regulation is stated in SOLAS regulation 19 and became effective 31 December 2004 (43). There are two types/ classes of AIS transponders: A and B. Passenger and commercial vessels will have a type A transponder, and smaller vessels can use a type B transponder. AIS information from a class A transponder will always be prioritized, and the signal from a class B transponder will only be shown if there is room on the AIS band. The AIS transponder works with a Global Positioning System (GPS) to broadcast the vessel's position. The signal is automatically broadcasted at regular intervals via the FM channels in the very high frequency (VHF) radio band. The frequencies used are between 156 and 174 Mhz. The transmit power for a VHF is limited to 25 Watts giving them a theoretical range of up to 100 km or 40-60 Nautical miles. However, a Class A transponder has a power limit of 12,5 Watts, but it is still possible to pick ut AIS signals 600km away with a satellite. Today are AIS data a vital tool for various industries and purposes. Examples of where AIS data is essential today are Port authorities, researchers, search and rescue, and the military.

An AIS transponder automatically transmits static and dynamic information, depending on the vessel's speed. Table 11 shows the transmitting frequency mentioned for the different classes and speeds. The static data relevant for analyses are typical: International Maritime OrgaNICation number (IMO), name, vessel type, and dimensions. Dynamic information includes UTC seconds, Speed over Ground (SOG), Position Coordinates (latitude/longitude - up to 0.0001 minutes accuracy), and Heading - 0 to 359 degrees. Class-A transponder transmits the signals using the SOTDMA protocol, which stands for Self OrgaNICed Time Division Multiple Access. This system assigns each vessel a given time frame where one after the other transmits their information, each using its assigned time slot.

Transponder Type	Vessel's Moving Status	AIS Transmission Rate
Class A	Anchored / Moored	Every 3 Minutes
Class A	Sailing 0-14 knots	Every 10 Seconds
Class A	Sailing 14-23 knots	Every 6 Seconds
Class A	Sailing 0-14 knots and changing course	Every 3.33 Seconds
Class A	Sailing 14-23 knots and changing course	Every 2 Seconds
Class A	Sailing faster than 23 knots	Every 2 Seconds
Class A	Sailing faster than 23 knots and changing course	Every 2 Seconds
Class B	Stopped or sailing up to 2 knots	Every 3 Minutes
Class B	Sailing faster than 2 knots	Every 30 Seconds

Table 11: AIS transponders and theire updateing rate (44)

2.7.1 AIS data collection

AIS data is generally collected from base stations or satellites. A base station can collect AIS information from a radius of up to 60 Nautical miles if it is installed at a higher altitude. However, there are examples where base stations installed at mountain tops can track vessels within a radius of 200 Nautical miles. However, in the NSR are satellites most useful to collect AIS data. There are different satellite data providers, and in this thesis, two different databases were used to collect the AIS data. The two databases were the IMT database, which uses the Norwegian coastal admiNICtration (Kystverket) satellites, and the ASTD- database from Protection of the arctic marine environment (PAME). Unfortunately, the author has not been able to find which satellites or satellite programs are used in the PAME dataset.

2.7.2 IMT – Kystverket

Kystverket currently operates five microsatellites with AIS receivers. The first satellite was launched in 2010 under the AISSat-program, and the newest was launched in 2021 under the NORSAT-program. The Norwegian satellites orbit 600km above the Earth in a polar low earth orbit (LEO). A satellite at

600 km altitude will make approximately 15 revolutions per day and use around 90 minutes between each pass. Such lanes are often placed, so the satellite passes close to the North Pole, typically at 82º N. This means that ships north of 75º N come within the satellite's horizon at all its 15 circulation per day (45) . Since there are five Norwegian satellites, will they be able to track vessels in the arctic and Norwegian sea areas at best every 20 minutes (46). The sample rate for the satellite is not defined in any of the sources. AIS data from Kystverket include all the static and dynamic information.

2.7.3 PAME – ASTD

Arctic Ship Traffic Database (ASTD) provided by the Protection of the Arctic Marine Environment (PAME) is based on AIS data from vessels operating in the arctic. However, the data is not limited to the arctic. The database provides information about the position, ice-class, ship's type, size, fuel specifications, and emissions. From class A transponder is the AIS data collected with a sample rate of 6 minutes. PAME do not give any information about which satellites they are using. However, their ASTD Data Document shows how AIS Class A transponder data from the USA supplements Norway's AIS Class A transponder data. Thus, they should be able to deliver a more detailed and more accurate coverage of ship traffic. The ASTD database collects approximately 4 million records every 24 hours, and they state that: The data in ASTD is very accurate, and data quality in ASTD is very high. The AIS data has been collected and stored in monthly CSV tables from 2012 to today. Data access is granted to eligible applicants at one of three access levels: Level I, Level II, and Level III. Level ll and lll are similar regarding what AIS information can be accessed. Both use a specific shipid that changes every month instead of IMO number/ vessel name or MMSI. Level l, on the other hand, includes IMO numbers, vessel names, and MMSI numbers. Lvl 1 data makes it possible to find specific vessels that are not anonymized. The raw data downloaded are not cleaned, and PAME recommends to filtered out all AIS Class A transponder signals from ships with less than ten positions in one month. This filtration means that ships with a sailing time of less than one hour in a whole month are filtered out and therefore not included in the final model.

2.8 Technical environment

This subsection will describe the technical solutions that were chosen for this thesis. Firstly, Python was chosen as the programming language. The programming language was chosen because it was where the author had the most experience. The advantage of Python's large variety of time-saving libraries able to analyze large data sets efficiently. The Python implementation was written in Jupyter Notebook, a free and interactive computational notebook that supports a combination of code and text. Combining text and its interpreted programming language makes it easy to test each step of the code and describe it in more detail. The interpreted programming language makes it possible to run each line of code, allowing one to check it and adjust it if needed immediately. Complex calculations and massive datasets require a fast computer, and the computer provides 32 Gb RAM, 1 Tb SSD, Intel i9 processor (4.5 GHz), and an external Graphical Processing Unit. The processor was crucial to effectively calculate the RIO values.

The following list is a concatenation of the main libraries and other pre implemented code used in this thesis:

- **Pandas** is a data analysis and manipulation tool. The package can be used to make DataFrames, reading, writing data, label-based slicing, fancy indexing, and subsetting large data sets. Pandas makes working with large data sets fast and easy, which is crucial when working with AIS data. Another advantage is that many packages are designed to work with Pandas, making them more flexible.
- **Geopandas** is Python library to make working with geospatial data. GeoPandas work together with Pandas to extends the datatypes and to allow spatial operations on geometric types and can be used to visualize data on a map.
- **Matplotlib** is a comprehensive library for creating static, animated, and interactive visualizations in Python and is used to make and visualize different plots. Seaborn is another library to plot and visualize datasets, and it integrates closely with Pandas. Seaborn is based on matplotlib and is similar to making statistical graphics in Python.
- **Beautiful Soup** is a Python library used to tubtract data out of HTML and XML files and automating web scraping of data from websites.

3.0 Methods

In this chapter, the methodology executed in this thesis will be described. Figure 14 shows the overall model used to calculate the RIO combining different data sets. As can be interpreted from the flow chart, the model can be divided into three parts.

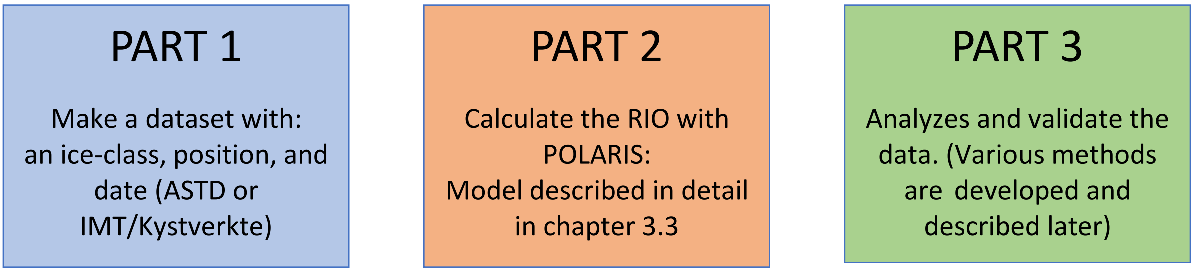


Figure 14: Model developed to analyze the data

1) The first part is to make a dataset with an ice-class, position, and date. This process varies depending on the desired outcome. The input can be historical AIS data from ASTD or IMT/Kystverkte, or a predefined route that can be manually plotted or based on historical data. This thesis takes the positions from historical AIS data in all calculations, and the dates and ice classes are adjusted in the prediction analyses.
2) In part two, RIO values are calculated based on the input from the first part, ice charts, and converting tables. The RIO calculator follows POLARIS described in chapter 2.3. The model can calculate the RIO for multiple points.
3) The last part analyzes and validates the RIO calculations.

The different data sets have been collected both automatically whit scrapping methods in Python and manually typing in the data. The ice-class in the RIO model is collected from the Northern Sea Route AdmiNICtration (NSRA) database, and the ice classes follow the Russian standard. The ice classes are converted to the IAC? standards with the use of conversion tables. The ice charts used in the model are from The Arctic and Antarctic research institutes from 2011-2021. These ice charts contain information about both the concentration and stage of development, which is one of the essential factors in calculating the RIO. The different dataset is saved in a CSV file format that's easy to work with in Python. Another important part of the model is to clean the different datasets. The cleaning process is discussed in further detail in chapter 3.1. After all the datasets are cleaned, they can be combined to calculate the RIO. The model calculates the RIO for multiple points or a route.

The branch called "satellite images" must be done manually and are used to control and validate the ice conditions. In addition, satellite images can be used to detect leads in the sea ice. It is possible to download the raw data from the satellites and analyze/ visualize this in Python. However, the Sentinel-hub program was used to analyze satellite images since the plugins and interface in the Sentinel-hub program are easier and faster to work with for control purposes. The following subsections are going through the RIO calculator, dataset, converting tables, satellite imagery, cleaning process, and validation.

3.1 Data collecting and cleaning

Data collecting and cleaning have been conducted manually and with web scrapping methods. It has also been essential to clean and filter the data effectively. Over 1 billion AIS data points were initially downloaded, and in total, over 700 000 RIO values has been calculated. This chapter discusses the collecting process and cleaning/ filtering methods used for the given dataset.

3.1.1 AIS data

AIS datasets are collected from two different databases. The first one is from Kystverket's historical data archive/ Department of Marine Technology (IMT) database. The second is the Arctic Council's Working Group on Protection of the Arctic Marine Environment (PAME), and their AIS database, the Arctic shipping activity database Special (ASTD). Permission must be granted to access both the AIS databases and the author has not been able to find open source AIS data where ice classes can be linked to the ice-class is included in the data. The main difference between the two data set is that the ASTD does not have the IMO number or other vessel-specific information. There are six values from these datasets that are considered in this thesis. The six relevant values are explained in table 12.

Parameter	**Details**
IMO number*/ ship id**	Unique for all vessels. The IMO number is used to pair the vessel with its corresponding ice class. The Ship changes every month
Longitude	Geographic coordinate. $(-180^{\circ}, 180^{\circ}]$
Latitude	Geographic coordinate. $[-90^{\circ}, 90^{\circ}]$
Speed over ground (SOG)*	Speed of the vessel measured in knots.
Timestap (unixtime)	The time when the message was sent. Unit is days since 1.Jan 1900, 00:00
Heading*	The compass direction in which the vessel's bow is pointed

*Ais data from IMT/ Kystverket, ** ASTD database

Table 12: AIS data from ASTD and IMT/ Kystverket used in the model

The vessels and the IMO number for the IMT/ Kystverket database were selected after researching open sources for potential vessels that had sailed through the NSR with lower ice classes. In addition to the open sources, old AIS data for the Kara Sea was used to find suitable vessels. In this AIS analysis, all vessels that had sailed across two lines in the eastern part were investigated in more detail. AIS data was collected from the IMT database for the vessels on the list. The data are then filtered and cleaned. The first step was to place a longitude and latitude limitation. The latitude limitations were set to include values between 69 and 83 degrees, and the longitudinal limitations were set to include values between 55 and -163 degrees. Next, duplicates and rows with missing values or sog values under 0 or over 22 knots were deleted. The ice classes used in the final dataset were the Russian standard, and the information from SeaWeb was only used for a separate analysis. The last step was to pair the IMO number with the suitable ice-class from the ice-class dataset and convert it to FSICR - IACS format. This was done using Table 6 and 7. This method is the same used in other studies (12). Finally, the cleaned and filtered dataset was sorted and saved as a CSV file.

The second AIS database was collected from the Arctic Council's Working Group on the Protection of the Arctic Marine Environment (PAME) and their AIS database Arctic shipping activity database (ASTD). This data does not have an IMO number but instead has a unique ship ID every month. The data set contains the ice-class. However, it is not stated where the ice-class is taken from or if they are converted. The author assumes it is the original ice class, and the Russian vessels do not have an assigned ice-class in the database. The data can be downloaded as monthly data covering the entire world in one CSV file. Therefore, it is necessary to filter and clean this data before it is used in the model. The first part follows PAME's recommendations, filtering out all signals with less than ten positions in one month. This filtration means that ships with a sailing time of less than one hour in a whole month are filtered out and therefore not included in the final dataset. Duplicates and data points without ice-class or positions were also removed from the dataset. Then a longitude and latitude limitation was placed. The latitude limitations were set to include values between 69 and 83 degrees, and the longitudinal limitations were set to include values between 55 and -163 degrees. After the filtering and cleaning process was completed, the monthly files were merged into a yearly dataset.

3.1.2 Ice-class database

The ice-class is critical in calculating the POLARIS RIO, and the ice-class is not included in the original AIS data. It is, therefore, necessary to find another database to gather the information. The northern sea route admiNICtration has an open-source archive of all the vessel's permissions for navigating the Northern Sea Route. This archive contains vessel information, including Ice class, vessel name, and shipowner. There is also possible to get the IMO number from an attached PDF. Unfortunately, the IMO number cannot be copied from the PDF but must be written manually to the final dataset. The data collection had to be done manually for over 4000 vessel applications to get a complete dataset linking the ice-class to the IMO number. This data collection is extremely time-consuming, and there are possible and easy to make typing mistakes. Since the AIS data contains the vessel name, there could be an option to match different datasets by the vessel name instead of the IMO number. However, there is easier to automate, but this method has a more significant potential for error. In this case, the dataset was made by copying the NSRA website information directly without the IMO number. The IMO number was added manually in an Excel document before it was converted to a CSV file used in the end model.

The data were first filtered and cleaned. First, IMO numbers with more or less than seven digits were deleted. The database contains rigs and barges that use a Russian standard similar to IMO numbers, but the numbers are usually six digits. Next, IMO number duplicates were deleted since a vessel has to apply for each voyage in the NSR. Lastly, rows with nan values for the IMO or ice-class were deleted.

After the data was cleaned, FSICR/ IACS ice classes were added from Sea Web to all non-Russian vessels. The new ice classes were manually added for each IMO number, and 392 new ice classes were added for the validation analysis. The new ice classes were the ice-class a vessel was given when it was built, and this was added to be able to analyze irregularities between ice-class standards.

3.1.3 Ice charts

Ice charts can be downloaded from the Arctic and Antarctic research institute (AARI) in SIGIRD-3 format for the whole Northern Sea Route. Five different ice charts have to be used to be able to cover the NSR: the Kara Sea, East Siberian sea, Barents sea, Chukchi Sea, and Laptev sea. The Barents Sea is not included in the official NSR, but it is included since it is an important area for the transit routes. The ice charts can be downloaded directly from ARRI, and it is possible to download charts from the last 25 years. It is also possible to download the ice chart in PNG format to visualize the ice condition and concentration. In this thesis, the ice charts were downloaded using Python and Beautiful Soup library and the module urlib. 2600 Ice charts were downloaded to the final model. First, beautiful soup lists all the files that can be downloaded. This list is made by reading the HTML code, and the urlib is then used to download all the charts as zip files. The charts are unzipped, and the variable polygon codes are loaded for each file. The values for density, stage of development, form, and shape file are extracted and converted in python for further use in the primary model. Missing values are assumed to be the most extreme value possible, and this is added to the dataset. A remark stating that this was not the actual value was then added to the assumed values.

3.2 Converting tables

An essential input to the final model is converting tables. These tables convert the different data to a uniform and standard form. For example, the two different AIS datasets use two different standards for ice classes, and both standards are therefore converted to the FSICR/IACS ice-class standard as this is used in POLARIS. As discussed in chapter 2.4, different methods of converting ice classes can be used, and the IMO-POLARIS method was selected. This method is also the most conservative model to convert the ice class. For FSICR ice classes is Table 7 used. The dates for the AIS data must also be converted and matched to the closest dates where an ice chart was published. This convertion table was made manually in excel. Other important convention tables used is: is converting SIGRID-3 format to the egg code format used in POLARIS (Table 10) and converting the ice-class and the ice regime to the Riv in POLARIS (Figure 7) .

3.3 RIO calculation

Python is used to calculate the RIO by combining all the datasets mentioned above. The model is based on Nabil's model but is further developed for the whole NSR. First, all datasets are loaded as CSV into python with the Panda package. Then, an RIO calculator takes information about the position, ice-class, ice data, and the converting tables to calculate the RIO based on the approach detailed in chapter 2.4. Figure 15 shows the model. Then the RIO can then be calculated for the data points using equation 1 and values from figure 7. In this thesis, over 400 000 RIO values were calculated using this model.

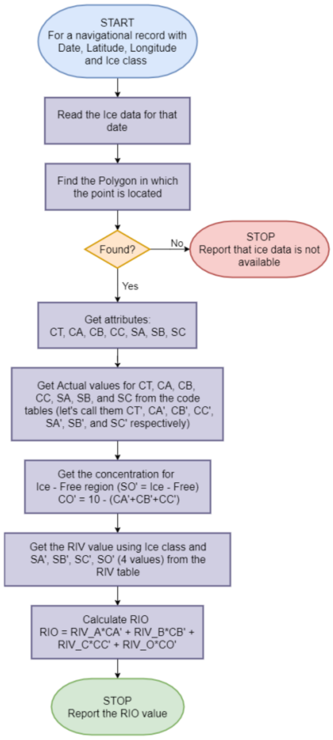


Figure 15: RIO calculation model

A dataset with multiple dates, longitudes, latitudes, and ice classes is loaded into Python with Pandas, before the longitude and latitude are converted from EPSG 4326 to EPSG 6078 format. The following method calculates the RIO for each point in the dataset. First, is the date used to read the closest ice chart for the right area. Then, a converting table is used to convert the date to the nearest date when an ice chart is published, and west and east limitations are used to find the correct ice chart. Next is to find the right polygon in which the point is located. If the polygon is not located, it reports "no ice data avialble" and the model starts the process for the next point in the dataset. On the other hand, CT, CA, CB, CC, SA, SB, and SC are saved to the dataset if the polygon is found. Then the conversion tables mentioned in chapter 2.6.3 are used to convert from Sigrid-3 format to actual values used in POLARIS. These values are saved to the dataset as CT', CA', CB', CC', SA', SB', SC'. Next, the concentration for the ice-free region is calculated and added as CO', and equation 2 is used. RVs values from figure 7 are collected using the ice-class and SA', SB', SC', SO'. As described in chapter 2.4, summer or winter RIVs are used based on the date in the dataset. Finally, the RIO is calculated with equation 1 and the result is added to the final dataset.

$$CO' = 10 - (CA' + CB' + CC')$$

Equation 2: Concentration for open water

After the RIO is calculated, the data quality must be analyzed before the datasets are considered in the final analysis. The data datasets can include incomplete data, errors, or wrong calculations. The main problem is when an ice chart only includes the ice concentrations without a stage of development. As discussed earlier, the code uses the most severe possible solution, which often results in an extreme value not representing the actual ice conditions at the given point. However, a remark is added where an assumed value is used, making it possible to filter out these values afterward. Another important consideration is that the total concentration must be equal to the sum of the partial concentrations. If not, it indicates an error in the input data or missing information regarding the partial ice types.

Equation 1 is the maximum RIO possible -80. The maximum RIV value is eight (No ice strengthening in heavy multiyear ice). If an RIO value is over -80 or the concentration is over, it indicates incomplete data or an input error.

3.4 Satellite images

Satellite images are important for better validating the data and understanding the actual risk picture. A methodology to detect vessels and visualize the ice conditions was developed and is described in the following subsections. The satellite images can be divided into two categories when it comes to the type of image and two categories when it comes to purpose. The two types of images are SAR and optical. The optical is easy to understand and read, but it is useless in cloudy or foggy conditions. The clouds make it difficult to use optical satellite images because, as highlighted in chapter 2.1.1, the NSR is often covered by clouds or fog. When processing optical images from the Sentinel- 2 L2A satellite, either actual color or false color can be used. Typically, a false-color picture is the best way to analyze ice and detect vessels. The optical images can be displayed without any adjustments.

SAR data is the most important source of information for detecting vessels and operational ice charting nowadays. However, optimizing the data and the different polarization for vessel detection or sea ice classification is necessary. Sentinel Hub is used to visualize the satellite images and has the advantage that different satellites can be used. The interface is easy to understand, and it is also possible to do more advanced coding in the Java language if the visualization needs it. This script coding is especially relevant for ice mapping. For example, a cross-polarization model can be applied directly, making it easier to categorize different ice regimes. The other option is to download the raw data from the different satellites and use Python to visualize it. However, this would be more time-consuming, and new models/codes must be developed for ice chartering and visualization. The Sentinel Hub was therefore chosen as the preferred method and tool.

3.4.1 Vessel detection

When SAR data is used for vessel detection normal polarization (HH) is the preferred input if only one polarization is being used. A vessel can often appear with a star shape instead of a uniform object when a normal polarization is used, making it easier to differentiate the vessel from the surroundings. Detecting vessels by thresholding the VV or HH polarization is the easiest way to differentiate the vessel. However, it can be challenging to separate a vessel from sea ice using only single-polarization and thresholding. Therefore, this project developed a more complex method using cross polarisations.

As a more complex method, a script coded in Java was made to make it easier to detect a vessel and separate it from its surroundings. The best option was found when combining VV and VH polarization (Red channel: VV, Green channel: VH, Blue channel: VV), and weighing the different polarizations against each other. Some vessels reflect more VV and are therefore represented in the red and blue channels. Other parts of a vessel reflect more VH signals, resulting in green contours. This difference in reflection makes the vessel appear white on the final image and makes it easy to spot a vessel. VH is also reflected from the sea ice, but mainly irregularities are reflected in the VH band. The VH is represented in the blue channel and is weighted with a value of 1.8, making it easy to detect leads or irregularities. The red channel mainly reflects the earth (soil, mountains) and is limited to only highly reflected values above 0.6. The green channel is limited to 0.9. One additional method was also developed for areas visited by the VVVH satellite (the south part of the NSR), which results in better resolution. The code developed for this is placed in Appendix A.

3.4.2 Ice mapping

Commonly, only one polarization is used to visualize the SAR data for ice conditions analyses. The use of one polarization is used primarily because of the lack of suitable methods to utilize cross polarisation. However, Martin Raspaud and Mikhail Itkin have developed a model taking advantage of cross-polarization in sea ice mapping (32). The sea and sea ice are presented in the blue spectrum through the HH polarization, and peculiar features are shown in red, taken from the HV polarization. The green is added to keep a pleasant overall palette and is based on the pegtop software recommendation (32). The green combines HV and HH, where HH is the top layer, and HV is the bottom layer. Mathematically this can be expressed:

$$Green\ channel = HV * (2 * HH + HV * (1 - 2 * HH))$$

Equation 3: Equation to calculate the green channel output

Noise is a huge problem when it comes to SAR images, and to be able to reduce the noise in the overall image, an offset is added to both HH and HV. This noise reduction is done with the following formula:

$$HV_m = \sqrt{HV + 0.002}$$

Equation 4: Equation used for noise reduction

Then the values must be normalized to make it easier to understand the effects of each color. The normalization is done when min and max values are set to the different channels.

Color channel	Min	Max
Red	0.02	0.10
Green	0	0.6
Blue	0	0.32

Table 13: Normalization of colors

Lastly, a 1.1 gamma correction is added to make the picture brighter. The code for this is placed in Appendix A

3.5 Validation of data

To answer the question *to which degree POLARIS, based on available ice information, can be used for planning purposes?* A methodology was developed to analyze and validate the available data. This methodology is described in the following subsections.

3.5.1 Comparison model of ice classes from NSRA and SeaWeb

Three different ice-class standards are commonly used for vessels operating in the NSR. Therefore, ice classes have to be converted from one standard to another. A challenge is when different operational limitations for ice classes are used. The difference in regulations is discussed in chapter 2.4. For example, the International Maritime Organization recommends the Polar Operational Limit Assessment Risk Indexing System (POLARIS) as an acceptable methodology to determine operational limitations in ice. Hence, the vessel can be designed with an IACs ice-class based on a POLARIS calculation for the given area. If the vessel is going to operate in the NSR will the ice-class be given a Russian ice-class to operate in the NSR. The conversion can result in different operational limits. The difference between national regulations in the NSR and international regulations for operations in ice is discussed in detail by Nabil (12). Previous studies have used the NSRA ice classes and converted them to POLARIS. However, this has been done for higher ice classes, as discussed in chapter 2.4. It is more difficult to convert between the lower ice classes. The main reason to use the NSRA database is that this is an open-source database with all vessels operating in the NSR.

Figure 16 shows the comparison model for ice classes from the NSRA and SeaWeb. 392 vessels with lower ice-class (<Arc 5) were analyzed in this model to find how accurate converting tables 6 and 7 were in determining the right ice class. The assumed ice-class was marked green according to converting tables 6 and 7, and deviation from tables 6 and 7 was calculated for each ice class. The deviation from the converting table gives valuable information about how ice classes are converted from one standard to another when actual ice-class regulations are used.

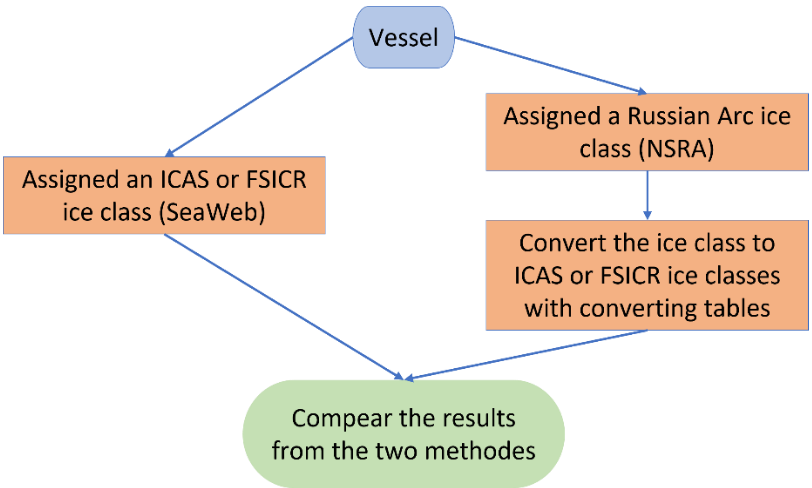


Figure 16: Model used to compare assigned Russian ice-class to IACS ice-class assigned by classification society

3.5.2 Comparison of AIS data from ASTD and Kystverket

It is interesting to evaluate the two AIS databases and investigate their characteristics. To substantiate an evaluation of the data quality, one can consider the number of data points, sample rate, and visualization for the same voyage in the two datasets. All these methods help to understand better the strength and weaknesses of the two datasets and how the data should be used in further analyses. Figure 17 illustrates the model used to evaluate and compare the two databases. Shipids from the ASTD database are manually matched with the correct IMO number from Kysverket/IMT for a given month. This matching is done by plotting the two databases with GeoPandas and making an interactive map where a colored dot represents a specific AIS position from a given dataset. The IMO number/ Ship id is added to the point. From the interactive map, can shipid and IMO numbers be matched manually based on similar sailing routes/patterns. Only the assumed corresponding vessels are then plotted on a new map to verify if the whole voyage matches. If this is the case, the data will be added to a final dataset for a more detailed evaluation. This process is iterative and time-consuming, and it resulted in 14 matched voyages and over 150 000 data points.

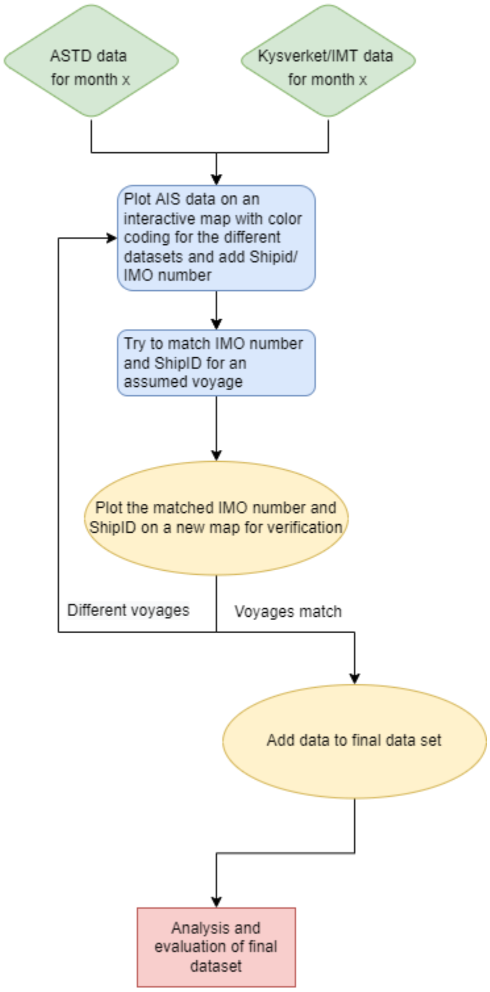


Figure 17: Model used to match voyages from ASTD and IMT/Kystverket

The quality of the two datasets is evaluated based on three parameters. The first is the sample rate, which explains how often an AIS signal is recorded. This sample rate is equal to the average/ maximum resolution of the dataset. The sample rate and the resolution between the dataset are calculated with by dividing data points from IMT/Kystverket on ASTD. Chapter 2.7 contains the AIS regulations linking speed and the transmitting frequency discussed. The sample rate delta vs sog can be plotted to determine if the datasets record data according to the regulations about transmitting frequencies. However, the ASTD database does not include the sog. This must be calculated separately based on the distance and time between two data points. The sog between two data points can be calculated with equation 5.

$$a =$$

$$\sin^2\left(\frac{\Delta lat}{2}\right) + \cos(lat1) * \cos(lat2) * \sin^2\left(\frac{\Delta long}{2}\right)$$

$$Distance = (2 * atan2\big(sqrt(a), sqrt(1 - a)\big) * R$$

R=6373km

$$SOG = \frac{\Delta Distance}{\Delta time * 1{,}852}$$

Equation 5: Sog calculated from AIS input

The second method to evaluate the data is by comparing the total number of data points. IMT/ Kystverkethas five satellites, and ASTD combines Norwegian and American satellites, but the number of satellites used is not mentioned. However, if the ratio between the total number of data points is different from the sample ratio, can this indicate a difference in coverage. This difference results from a higher revisiting time, resulting in fewer areas with no data. The last method used to compare the data in this thesis is by plotting the two datasets on a single map. The two datasets are plotted with different colors, red for IMT/ Kystverketand green for ASTD. By changing the plotting order, the coverage of the two databases can be visualized. The picture will be green or red if the datasets are precisely the same. The underlying layer will only be visible if they do not overlap. The visual representation, combined with the sample rate and the ratio between the total number of data points in a dataset, can be used to validate the quality and strength of the two datasets.

3.5.3 Ice charts

The quality of the ice charts will impact the result in the overall model. Therefore, it is crucial to have a methodology to analyze the weakness and strengths of the ice charts in this analysis. Furthermore, there is challenging to determine the thickness of sea ice from satellite data during the melting period. This should therefore be investigated. The information from the ice charts used in POLARIS is the stage of development and concentration. A stacked density plot for each week is plotted based on data from the last seven years, where the density values on the Y-axis is normalized. The data plotted are values with undetermined/ unknown values (99 in Sigrid-3 Format) and data with information about the stage of development. The total number of bins equals 52, the number of weeks in a year. In addition to the density plot, a map is made to investigate if the unknown values are related to a specific area. The map is made with Matplot. Stage of development and concentration are analyzed with this method. As mentioned in chapter 3.3, the RIO model assumes worst-case conditions when these conditions are undetermined. Therefore, it is vital to understand better how the ice charts limit the final model.

3.6 Historical AIS analysis

This section presents an evaluation methodology for RIO values calculated from historical AIS data. First, the RIO values are calculated with the RIO calculator described in chapter 3.3 for the historical AIS data from IMT/Kystverket and ASTD datasets. It is of interest to assess how vessels have operated based on POAIRS. This analysis can be divided into three parts with different goals. The first part of the analysis investigates if there is a correlation between ice-class and negative RIO values. Investigating the link between negative RIO values and ice-class is important to understand better their willingness to operate with higher risk based on POLARIS calculations. The second part examines if there is a correlation between the number of negative RIO values relative to the total number of points and the number of days to the closest ice chart. In previous studies, has the RIO only been calculated on the days when the conditions were published. However, old charts have to be used in the NSR for planning purposes since they are only updated once a week. Thus, it is interesting to investigate if negative RIO values increase and correlate with the number of ays to the closest ice chart. Hence, this can imply the conditions change fast in the NSR and result in outdated ice charts after a few days. The last part plots the negative RIO values on a map to determine if particular areas are extra challenging for a specific ice class.

The first and second parts of this analysis investigate if there is a correlation between RIO values and ice classes or days to the closes ice chart. The calculated RIO values for both datasets are loaded into Python with the help of Pandas. The first analysis is conducted using the value count function in Pandas for all ice classes with the following RIO values: RIO < 0, RIO < -10, and RIO < -20 and save the dataset to Excel. For the second analysis is delta days calculated by subtracting the date for the AIS point from the date for the ice chart used. Then the value count function in Pandas is applied for all delta days with the following RIO values: RIO < 0, RIO < -10, and RIO < -20, before the dataset is saved to Excel. Lastly, is the results plotted in excel as a multi-diagram.

Lastly, the calculated RIO values are plotted with Matplot for each ice class. Pandas are first used to filter the data on one ice-class, and values with undetermined or unknown ice conditions are filtered out. The plots consist of four main elements. The first is the map which is loaded from the gdp-datasets. Then RIO values are sorted into three categories: RIO < 0, 0 > RIO > -10, and RIO < -10 fallowing the operational limitations in POLARIS. Each RIO category is assigned a specific color pallet: Greens, autumn, or cool.

3.7 Combined analysis

The historical analyses resulted in a few voyages with negative RIO values. To further analyze why a vessel operates with a negative RIO, an analysis combing satellite images, ice charts for the same day, and AIS data were combined. The data was collected with previously explained methods. The AIS data was selected because the ice chart was published the same day the vessel operated with negative RIO values. Hence the ice chart and satellite image should present the same ice conditions. First, a voyage is selected based on the criteria mentioned above. The AIS data is then plotted with Folium on a map and saved as JPG. Then the ice chart is plotted on a new map where concentration and stage of development are color-coded. This map is also saved as JPG. The last part is to use the methodology described earlier. The vessel is located and marked following the method in subsection 3.4.1. After this, the Javascript for cross-polarization described in subsection 3.4.1 is applied. The image is downloaded as a JPG. The three pictures are laded into Photoshop as a stack with the script function (bottom layer: satellite image, Middle layer: ice chart, and top layer: AIS data). They are aligned based on the land area. Then the “action” function is used to automatically delete everything from the AIS picture except the track and the marking. The fill is adjusted to 75% for the ice chart. The color blending is changed to “color,” making it possible to display the satellite image.

3.8 Predict future operations

A new methodology had to be developed to investigate to which extent it is possible to use historical data to predict and plan a voyage based on POLARIS. First, it is necessary to understand what input data and parameters are required for such a model. It is crucial to find where the data input is limited based on the previous validation and analysis before the predictive analysis is conducted. This chapter considers a case with a predefined route and ice data for 2014-2021. It is possible to change the input data for the route, and the model can then be used for other voyages as well. The first analysis investigates the median RIO along the route. Next, the route is plotted as a boxplot for the whole route. According to POLARIS, this is used to establish the operational season for vessels with different ice classes. The last method visualizes operational distribution along the route for each week. The most relevant periods are the melting and freezing periods for planning purposes. However, in the analyses of the ice chart, it was clear that data from the melting period can not be used. Therefore, this analysis focuses on the freezing period for the analysis of operational seasons.

3.8.1 Predefined route

Several different routes can be chosen when transiting the NSR. The most used alternatives are shown in Figure 18. A vessel's route depends highly on the ice condition combined with wind, waves, visibility, and temperatures when transiting. It is interesting to select a predefined route that is not going through the areas where vessels typically encounter higher RIO values. The historical AIS analysis is essential when a specific voyage is selected. Possible transit voyages for vessels with lower ice classes are plotted from old AIS data with Folium. The final route is chosen manually. The AIS data selected for this study is a voyage conducted by a container vessel with a lower ice class. The chosen route goes through the northern part of the Kara sea and through the Sannikov Strait, which is most commonly used when transiting the NSR. This transit route is also north of the areas where vessels, based on historical analysis, operate with negative RIO values.

Figure 18: Routs commonly used for transiting the NSR (47)

First, the RIO calculator calculates the RIO values along the route for a specific ice-class for all the ice charts published from 2014-2021. This results in a new dataset of around 100 000 RIO points for each ice class. This dataset is used in all the predictive analyses. Along the route, the vessel will be exposed to local areas of the sea ice, resulting in extreme values where the operator could have sailed around the ice field. The NSR admiNICtration can also assign an icebreaker through the area. It is impotence to recognize this. Therefore, extreme values outside the standard deviation should be considered with extra care. The median RIO is calculated for each point along the route in the first analysis. The median is used to minimize the impact of extreme RIO values . The new dataset with median RIO values for a given ice-class for a whole year is then plotted with Mathplot. Finally, the RIO values are visualized with an assigned color.

The second part of this analysis is data for each ice-class visualized in a boxplot for the relevant weeks when the season transforms from summer to winter. The parameter used in the boxplot is the median value, lower quartile, which is equal to 25% of scores that fall below the lower quartile value. The upper quantile equals 75% percent of the scores below the upper quartile value. The quantiles were selected to be able to filter out extreme values. The final plot was a red, yellow, and green color coding added to show the operation limits easily. RIO is plotted against the longitude in the final box plot. However, Since real AIS data is used and this data mainly depends on time instead of distance sailed, the time domain for the given voyage must be converted to longitude. This conversion results in a nonlinear x-axis. The plots for the different ice classes for a given week are then used to determine the predicted operational limit. The operational limit is changed when a boxplot's lower quantiles cross the line to a new operating limit. For example, if the lower quantile of a boxplot in week 50 equals an RIO of 5 the next week, this increases to an RIO of -2. The operational limit for normal operations will then be including week 50.

The last analysis visualizes the operational distribution along the predefined route for a specific week and ice-class. This analysis aims to understand the consequence better if an operation is moved in time. The data used is the median RIO for the specific point on the route. In contrast to the first analysis, this further filters the data on the week and ice-class instead of using average week values. Lastly, the median RIO values converted to operation permitted, ice breaker escort, ice breaker escort with limited speed, and operation not permitted using table 3. To validate the data, DNV recommended comparing the result of this last analysis to the old NSR rules for operation. Both with and without icebreaker escort are then compared.

4.0 Validation of data

4.1 ice classes from NSR admiNICtration and SeaWeb

RIO calculation needs an ice-class according to POLARIS. Still, ice-class information is not available in AIS data. There are several ways to collect this info. The NSRA and SeaWeb databases are examples of databases that determine the ice-class in two ways. SeaWeb uses the ice-class classification society, and The NSRA assigns a Russian ice-class when a vessel obtains sailing permission for the NSR. The NSRA is an open-source database that can be converted IACS/FSICR, and this method is investigated in detail. A comparison of the ice classes converted from the NSR admiNICtration to actual ice classes in the SeaWeb database is found in Tables 6 and 7.

Table 14 shows how a vessel assigned a Russian ice-class will be converted to IACS/FSICR with table 7. The green boxes are what should be expected from conversion tables 6 and 7, and it is of interest to find if there is a derivation from the converting tables. Hence, if Russian ice classes are used and converted, will this result in a different ice-class than the vessel assigned by the classification society. An example from table 14 is a vessel assigned an Ice 1 Class from the NSRA. From conversion Table 7 will this be converted to no ice-class(NIC) in the IACS/FSICR standards (green marked). However, only three vessels out of 58 were assigned a NIC by their classification society. Hence, for Ice 1 vessels converted, will there be a 95% derivation from the recommended conversion method. As seen in Table 14. The vessels will have higher ice classes (1C, 1D, or IS) if the ice-class from the classification society is used. In total, for all vessels investigated Table 14 shows a 20% deviation from what is recommended in table 6 and 7. In general, for vessels with ice classes, Ice 1 and no IC will conversion tables from Russian ice classes to IACS/FSICR often underestimate the ice class.

NSRA	Sea Web									
	1AS	PC 6	1A	1B	1C	FS Ice-classII/ 1D	Ice strengthened	No IC	**Deviation from recommended ice class**	***Total number of vessels***
Arc 5	8	2	3					1	***29 %***	***14***
Arc 4	1		133	1				3	***4 %***	***138***
Ice 3			1	12			1	2	***25 %***	***16***
Ice 2				1	24			1	***8 %***	***26***
Ice 1					25	29	1	3	***95 %***	***58***
No IC			3		1		5	131	***6 %***	***140***
Deviation from recommended ice class	***11%***	***0%***	***5%***	***14%***	***52%***	***100%***	***100%***	***5%***	***20%***	
Total number of vessels	***9***	***2***	***140***	***14***	***50***	***29***	***7***	***141***		***392***

Table 14: Russian ice classes assigned by the NSRA compared to IACS/FSICR ice classes (assigned by class societies) from SeaWeb. The green boxes are equivalent to the ice classes recommended in Tables 6 and 7. The numbers represent the vessels with the given ice class

According to Table 14, another aspect worth mentioning is that Arc 4 or Arc 5 can in a real-life scenario be converted to PC7 or PC 6. Still, Table 6 advises converting Arc 4 and Arc 5 to IAS or IA. However, the main problem is that the risk index value used in POLARIS distinguishes between risk values for PC7, PC6, IAS, and IA. To sum up, when a Russian ice-class is used from the NSRA and then converted to IACS/ FSICR, the converted ice-class will often derivate from the original ice-class assigned by the classification society.

4.2 Comparison of AIS data from ASTD and Kystverket

The delta in seconds for the difference in time between two consecutive AIS messages is shown in Figures 19 and 20. The delta distribution can be used as a resolution measure for the maximum resolution. A higher delta will typically result in fewer data points in total. Hence, a lower resolution. For example, the median delta is 12 sec for IMT/ Kystverketand 768 sec for the ASTD database, this equals a resolution of 1:64. However, a high delta does not automatically result in higher resolution for a dataset. Figure 19 shows how the ASTD data is filtered with a cut of around 360sec (6 minutes), which was expected from the ASTD document. Still, it was not expected that more data would be added to the final dataset with a delta of less than 360sec. There is also no change in delta for vessels with a sog over 14 knots for the ASTD data. On the other hand, there is no cut-off for the data from Kystverket, and the median delta for sog over 14 knots is 7 sec. This median delta value is close to the AIS regulations for class A vessels (6 sec/ ais signal).

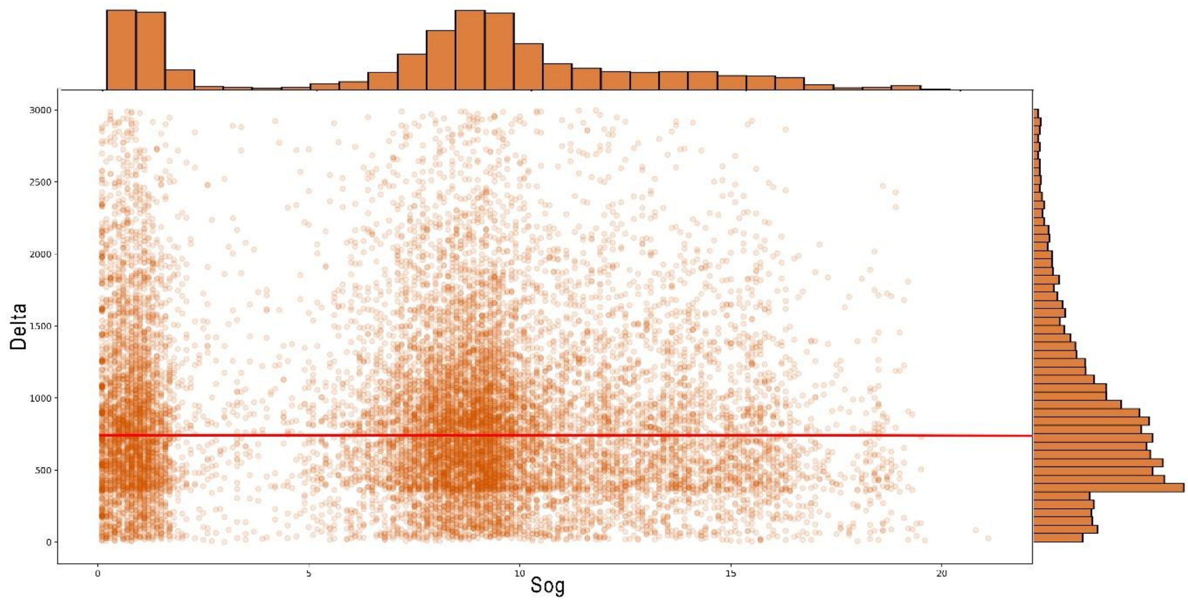


Figure 19: Scatter plot of the sog and delta (the difference in time between two consecutive AIS messages) for the ASTD database. Redline mark the median delta for the data set and is 768 sec

Figure 20 shows the sample rate delta plotted against the SOG for IMT/ Kystverketand the ASTD database. Seaborn distplot is used in combination with histograms. Comparing the median value and the scatter plots to AIS regulation discussed in chapter 2.7, the sample rate should increase for sog > 14 knots. As a result of this, can it be assumed that the datasets should have a higher density in the lower right part of the scatterplot. As mentioned above figure 19 shows that this is not the case, and there is no correlation between the sog and the sample rate for the ASTD database. Thus, the resolution/ accuracy of the data will decrease when a vessel is operating with a higher SOG. However, figure 20 has a higher density of pints than expected, according to the regulations in Table 11. The orange area represents sog < 14 knots. The red line is the median delta of 12 sec (10 sec in the regulations), which can be expected from table 11 for type A AIS systems. The green area represents sog > 14 knots, and the median delta is 7 sec (6 sec in the regulations). Thus, the sample rate is almost the same as stated in the regulations in table 11.

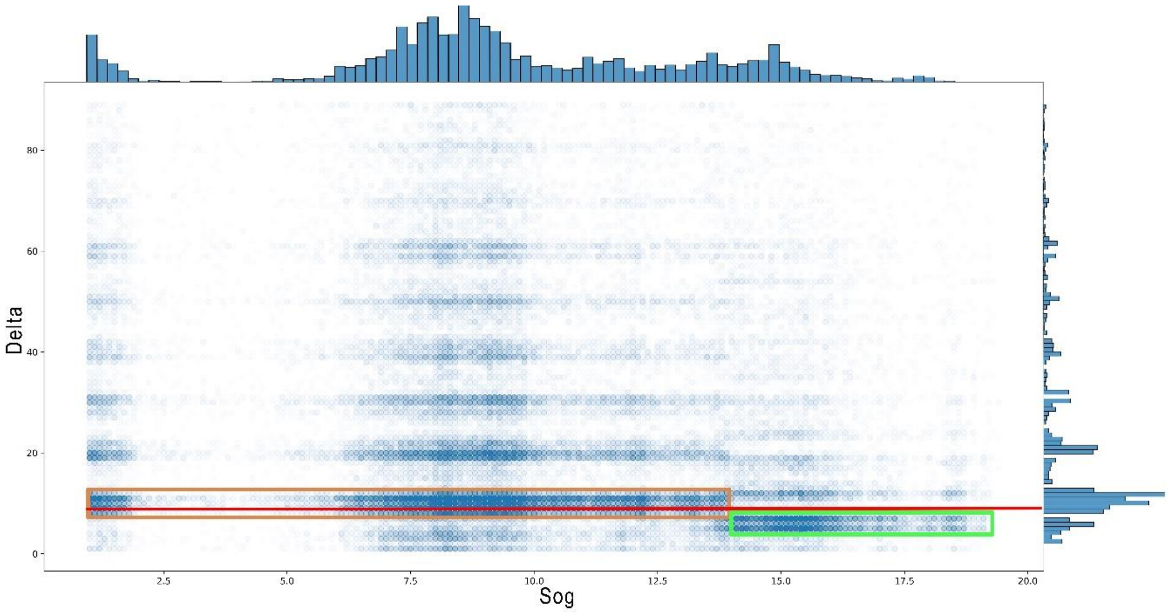


Figure 20: Scatter plot of the sog and delta (the difference in time between two consecutive AIS messages) for the IMT/Kystverket database. Redline mark the median delta for the data set and is 12 sec. The orange box marks the recommended (table 11) sample rate for sog < 13knots, and the green is for sog >13 knots

Table 15 shows data points from the two databases listed for the same vessels in the same month. The difference between the two databases is 1: 9.89, which emphasizes a smaller difference between the two datasets compared to the delta calculations. Figure 21 shows the ASTD and IMT/ Kystverketdatabases plotted on the same map. This picture illustrates the difference between the two datasets. Furthermore, figure 21 shows why the two other comparison methods mentioned above give different results. The reason for the difference in the resolution is the revisiting time for the different satellite programs. Hence, the gaps equal a minimum of 20 minutes between each series of data points in the IMT/ Kystverketdatabase.

Year- month	**AIS messages received inKystverket/IMT**	**AIS messages received in ASTD**	**Ratio** $\left(\frac{Kystverket\ /IMT}{ASTD}\right)$
2014-07	564	90	6,27
2016-07	1108	133	8,33
2020-09	33071	5017	6,59
2020-10	69939	5017	13,94
2020-11	23361	2681	8,71
Total number of records	**128043**	**12938**	**9,89**

Table 15: Comparison of AIS messages received from IMT/Kystverket and ASTD from the same voyages

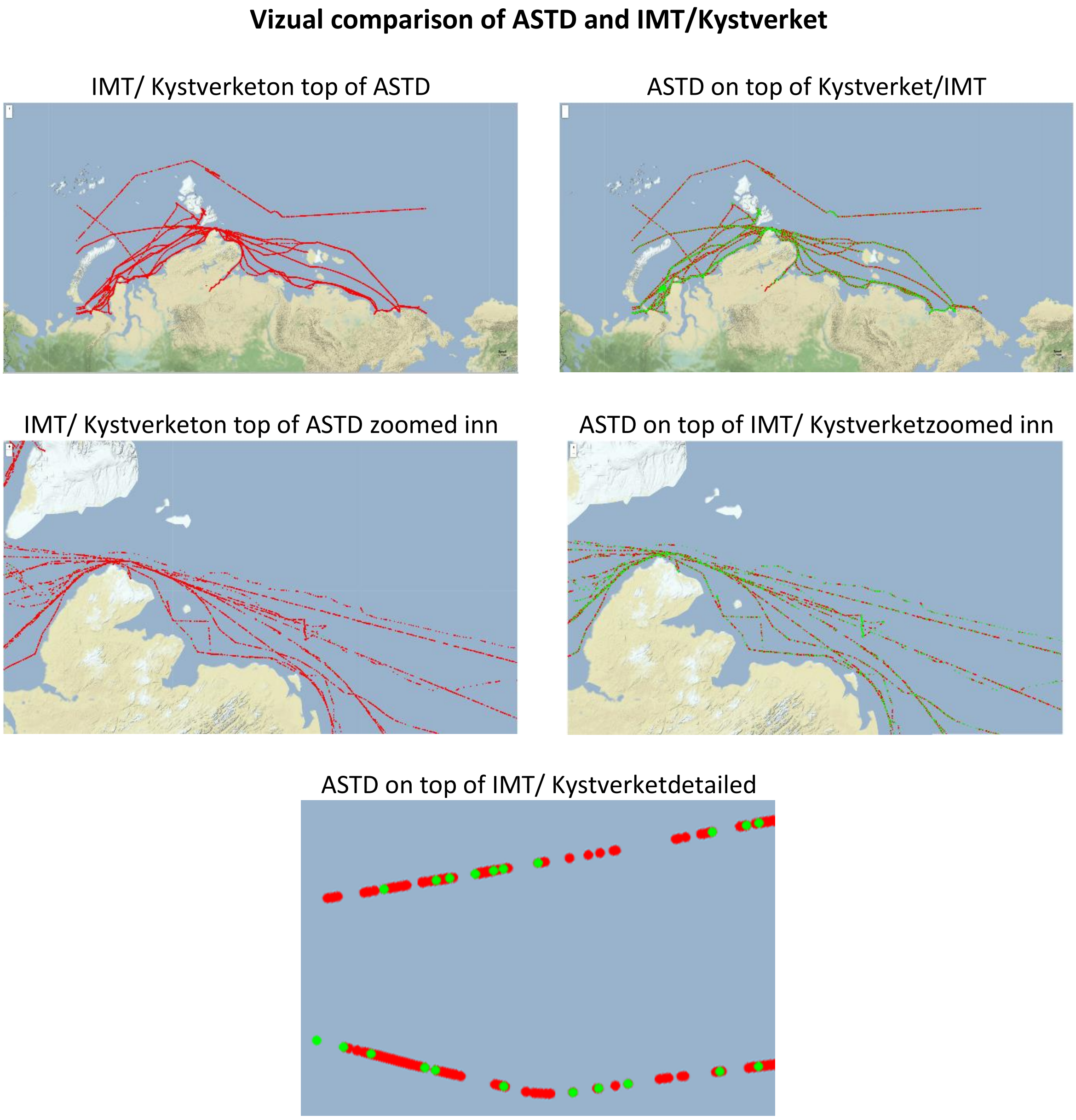


Figure 21: Vizual comparison of AIS messages received from IMT/Kystverket and ASTD from the same voyages

4.3 Analysis of ice charts

The RIO model is highly dependent on the performance and quality of the data from the ice chart. As discussed in chapter 2.5, observations of sea ice thickness remain limited when sea ice is covered with water ponds under the melting phase. Therefore, studying the data to see if there are areas or periods where the data deviates from the normal is interesting. Figure 22 shows a density plot comparing each week to the total number of locations. A density of one means that all locations had information about the stage of development. From figure 22 there is a distinct trend between week 21 and week 29 where the data about the stage of development are missing (SIGRID-3 code 99). According to A. Rösel, L. Kaleschke, and G. Birnbaum melt pond fraction for the entire Arctic show a strong increase in June and reaches a maximum in July (22). Hence, the development and concentration stage can be challenging to determine in this period. As seen in figure 22, this is also a challenge for AARI ice charts. However, there are only 3 locations out of 100 000 where the concentration was unknown/ undetermined.

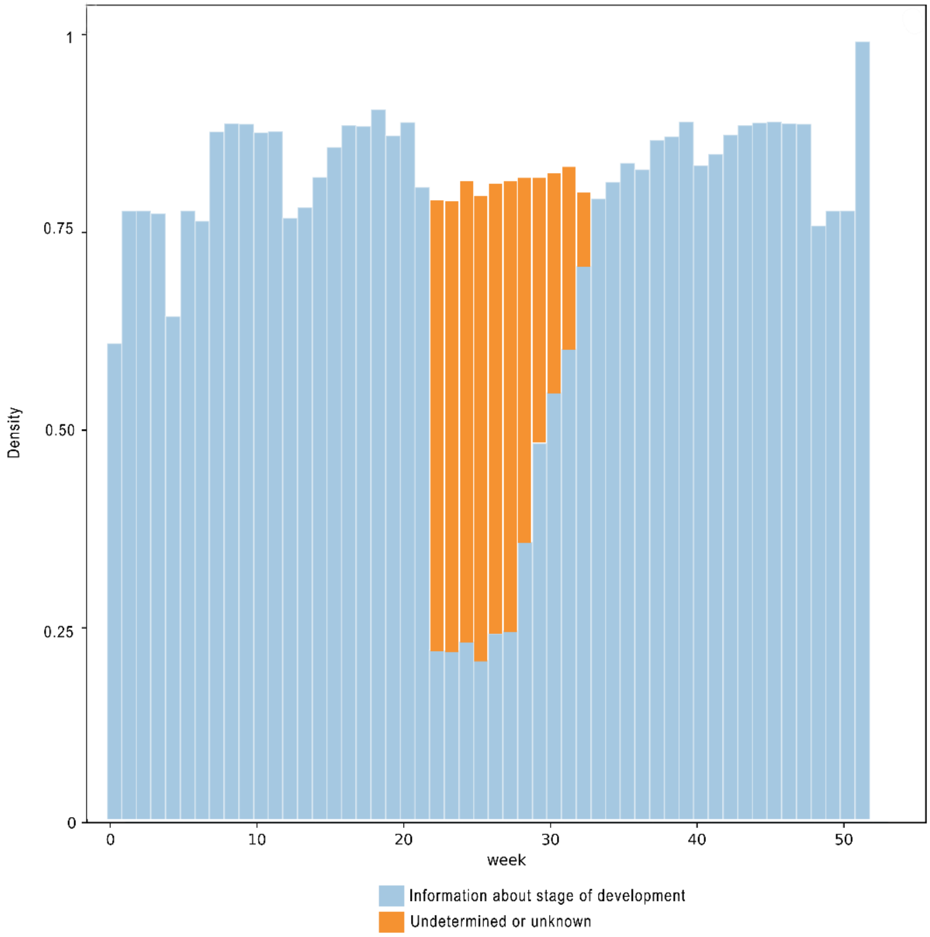


Figure 22: Density plot of the information about the stage of development for ice charts in the NSR. Blue = ice information about the stage of development, Orange = unknown/ undetermined stage of development. The X-axis is the week number, and Y-axis is the density compared to the week with the most points (week 52)

In contrast to the clear trend in figure 22, the missing data occur in the hole NSR, as seen in figure 23. Therefore, there is a clear limitation when ice data from week 21 to week 29 are used. However, this limitation is expected. ARRI has stated that Russia only provides parameters of interest, which is concentration, in their ice charts during the summer season. In Russia, a distinction is made between winter ice charts (ice type, form, concertation, etc.) and summer charts with concentration only. However, there is possible to estimate the stage of development based on linear regression or worst-case estimations. A worst-case approach where heavy multiyear ice has been assumed for these ice conditions has been used in other RIO analyses (12). However, this will result in extreme RIO values that are not representing the actual ice conditions. Hence it is not easy to conduct a precise and accurate analysis of the RIO in the melting phase, where a vessel with a lower ice-class can expect operational limitations if heavy multiyear ice is assumed.

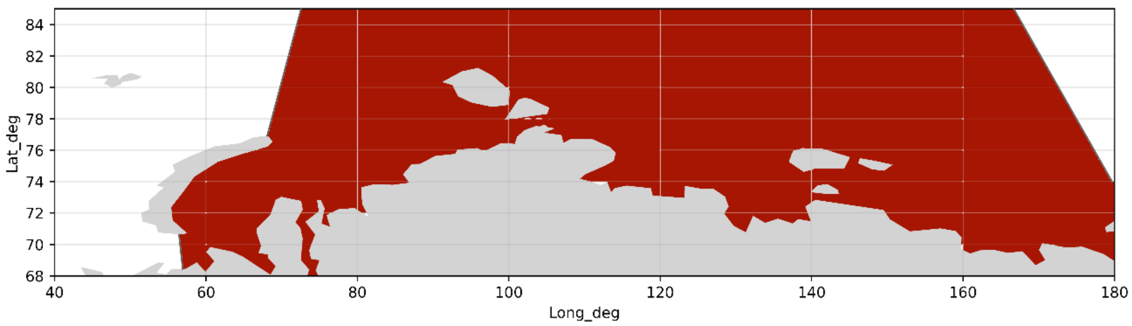


Figure 23: Areas where the stage of development is undetermined/ unknown between 2014 and 2021.

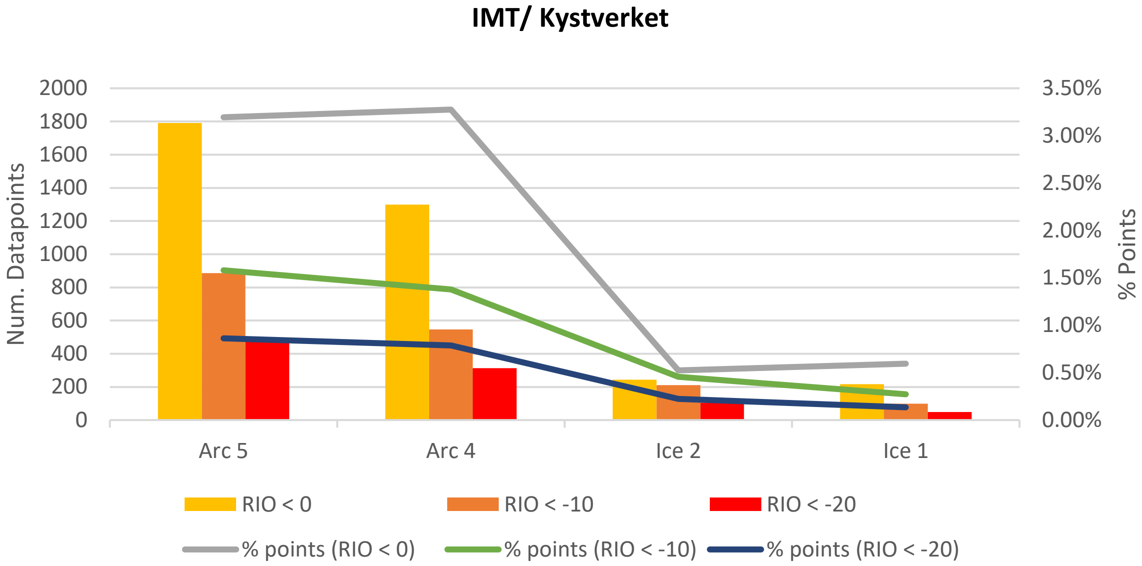
5.0 Results and discussion

5.1 Analysis of historical AIS data

This chapter performs historical RIO simulations with the developed method and Python model. From the performed simulations can areas and trends be investigated further. Along the NSR, will the vessel be exposed and operate with different RIO values. To better understand the risk picture for operations in the NSR is historical AIS data combined with historical ice charts to calculate RIO values for old operations. Based on the initial 150 million AIS message records, over 300 000 RIO values for relevant vessels from 2014 to 2021 were calculated.

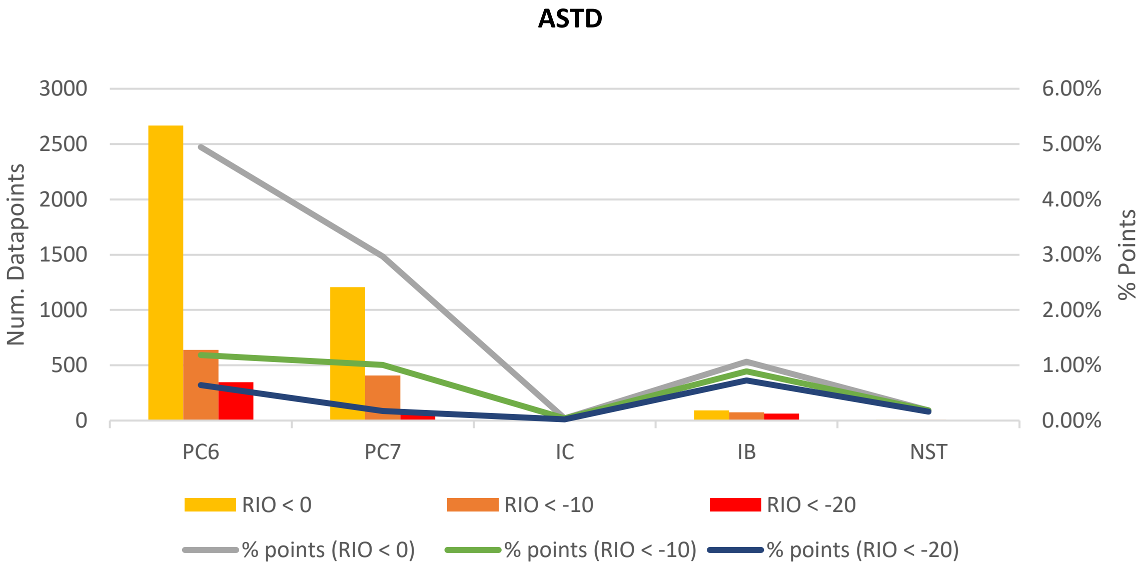
To better understand a vessel's willingness to operate with negative RIO values, the number of data points for the different RIO values are analyzed in Figure 24 and Figure 25. The percentage of points with a given RIO indicates how often a vessel with a given ice-class operates with an increased risk based on POLARIS. For example, when comparing class B and class C vessels with an RIO < -20 for both datasets, class C vessels are statistically operating with an RIO < -20 in 0.19% of the time, for a class B vessel, is this 0.64% of the time. Thus, a three-time higher chance that a vessel in category B will operate with an RIO under – 20. However, almost all the negative RIO values for the class C vessels in table 25 for the ASTD database are located in the Kara Sea, and for vessels not transiting the NSR. The data in figure 24 are therefore more representative of transit voyages.

Regarding planning purposes, vessels with lower ice classes will in 99,45% operate within their RIO limits based on calculations from ice charts and AIS data from 2014 to 2021. This result does not include vessels that have operated with an ice breaker. Thus, the actual number will therefore be even higher. At the same time, ice load within the operational limits can results in dangerous situations where the vessel is exposed to unexpected high ice loads. The operational risk index from POLARIS only indicates if a vessel is recommended to operate in the ice regime. Hence, POLARIS does not determine the risk (probability*consequences). There is no difference in RIO between cargo and passenger vessels. How much ice loads the vessel is exposed to is also much up to the navigator and the crew. According to IMO, sailing in apparent safe areas in terms of positive RIO does not mean that there is no danger. Two out of three accidents investigated in the NSR had positive RIO values when they occurred (49).



Ice class	Tot Data points	RIO < 0	% points (RIO < 0)	RIO < -10	% points (RIO < -10)	RIO < -20	% points (RIO < -20)
Arc 5	56006	1790	3.20 %	885	1.58 %	483	0.86 %
Arc 4	39658	1299	3.28 %	546	1.38 %	312	0.79 %
Ice 2	46353	243	0.52 %	211	0.46 %	104	0.22 %
Ice 1	36369	216	0.59 %	99	0.27 %	49	0.13 %

Figure 24: The relative distribution of data points for different RIO value ranges and ice classes for the IMT/Kystverket database.



Ice class	Tot Datapoints	RIO < 0	% points (RIO < 0)	RIO < -10	% points (RIO < -10)	RIO < -20	% points (RIO < -20)
PC6	53967	2669	4.95 %	639	1.18 %	346	0.64 %
PC7	40632	1207	2.97 %	409	1.01 %	71	0.17 %
IC	22756	9	0.04 %	9	0.04 %	5	0.02 %
IB	8541	91	1.07 %	76	0.89 %	62	0.73 %
NST	3774	7	0.19 %	7	0.19 %	6	0.16 %

Figure 25: The relative distribution of data points for different RIO value ranges and ice classes for the IMT/Kystverket database.

5.1.1 RIO VS ice charts

As described in Chapter 2.6, the ice charts for the NSR are updated every week. Therefore, considering how the RIO values change with time to the closest ice chart is of interest. Figure 26 shows no distinct correlation between the percentage of potions with negative RIO values and time to the closest ice chart. The percentage of points also varies between the datasets, and no clear trend can be established from the data. The author had assumed the ice chart for day -1, 0 or 1 to be the most accurate. Hence, the lowest % of relative points. However, the relative number of RIO values does not decrease for day -1, 0 or 1. The lack of correlation can be a result of different factors. For example, winter ice conditions might have worsened since the last ice chart. Still, ice conditions might have improved in the summer since the previous ice chart when the ice is melting, and there is more ice drift. It can therefore be beneficial to investigate the two seasons separately.

From a planning perspective, is it positive that the relative distribution of negative RIO values does not correlate with the time until the closest ice chart. This lack of correlation can also result from vessels often operating in an ice channel where there is little drift ice between the continental coastline and the ice edge for the massifs of multi-year ice. According to Tadeusz Pastusiak, there is a 90.9% probability of occurrence of an ice-free water corridor during the peak of the summer navigation season (9). Another explanation that emphasizes the predictable conditions is the long-term Russian hydrometeorological forecasts covering 2–5 months. The forecast has proved helpful for vessels with lower ice-class. The reliability of forecasts regarding types of ice navigation conditions is approximately 85% for all the NSR (50) (51). Lastly, the lack of correlation can also result from ice maps being too general and simplifying the actual conditions.

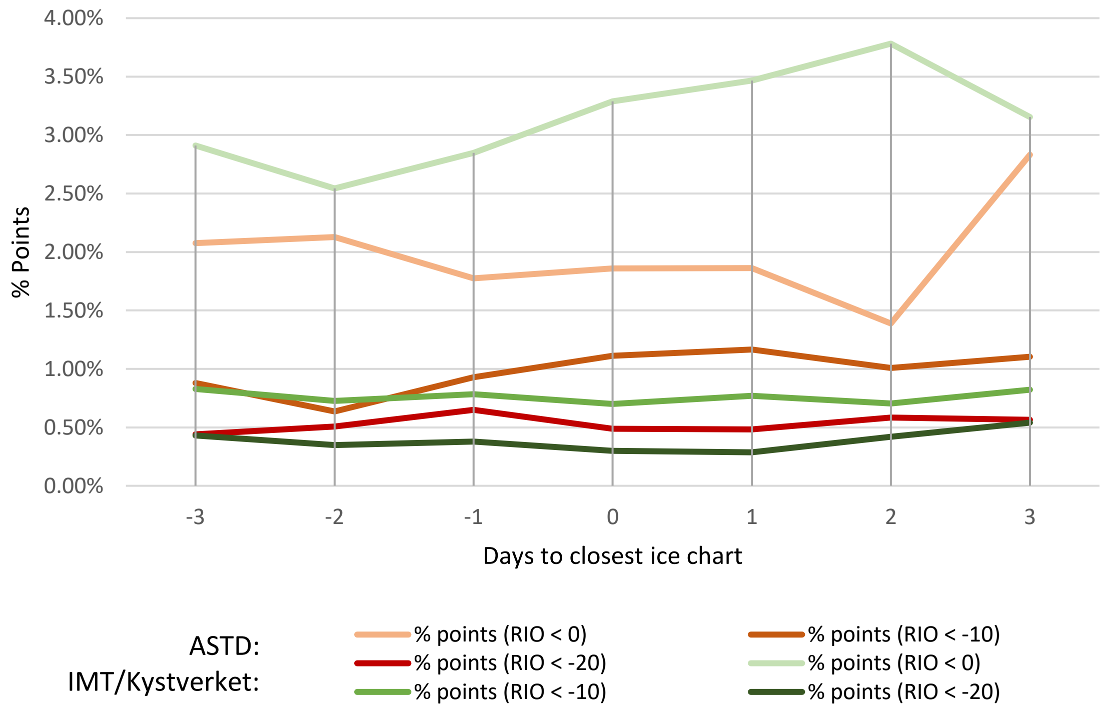


Figure 26: Percentage of negative RIO values for the number of days to the closest ice chart. Red/orange represents data from the ASTD database. Green represents data from IMT/ Kystverket

Days to closest ice chart	Num. Datapoints	RIO < 0	% points (RIO < 0)	RIO < -10	% points (RIO < -10)	RIO < -20	% points (RIO < -20)
-3	25206	523	2.07 %	222	0.88 %	111	0.44 %
-2	25628	545	2.13 %	163	0.64 %	130	0.51 %
-1	25089	445	1.77 %	233	0.93 %	163	0.65 %
0	24369	453	1.86 %	271	1.11 %	119	0.49 %
1	25136	468	1.86 %	293	1.17 %	121	0.48 %
2	26718	371	1.39 %	269	1.01 %	156	0.58 %
3	26240	743	2.83 %	290	1.11 %	148	0.56 %

Table 16: IMT/Kystverket data for the number of days to the closest ice chart, number of data points for a given RIO range, and the percentage relative to the total number for the given number of days

Days to closest ice chart	Num. Datapoints	RIO < 0	% points (RIO < 0)	RIO < -10	% points (RIO < -10)	RIO < -20	% points (RIO < -20)
-3	18095	534	2.91 %	152	0.83 %	79	0.43 %
-2	17732	451	2.54 %	129	0.73 %	62	0.35 %
-1	17459	497	2.85 %	137	0.78 %	66	0.38 %
0	18425	606	3.29 %	129	0.70 %	55	0.30 %
1	17802	617	3.47 %	137	0.77 %	51	0.29 %
2	18351	694	3.78 %	129	0.70 %	77	0.42 %
3	18511	584	3.15 %	152	0.82 %	100	0.54 %

Table 17: ASTD data for the number of days to the closest ice chart, number of data points for a given RIO range, and the percentage relative to the total number for the given number of days ASTD

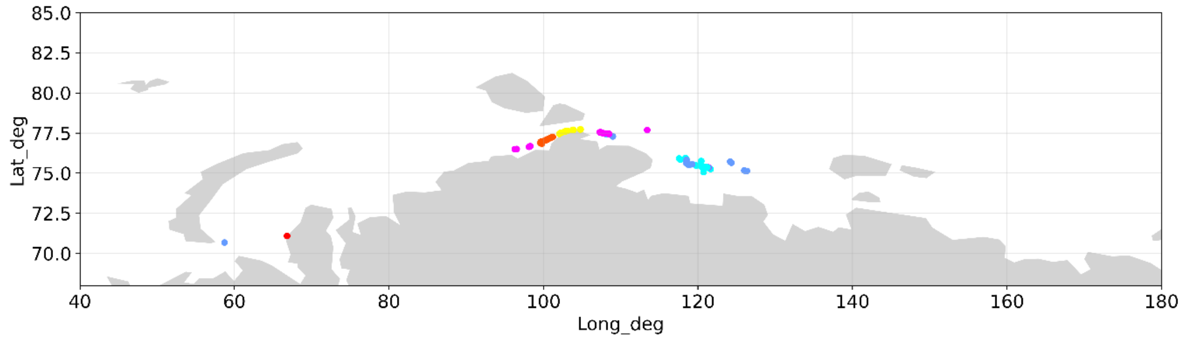
Figure 26 illustrates the different risk patterns for ice classes lower than PC7. If the ice data were correct, there were 23 instances when a vessel operated with a negative RIO outside its operational limit. As visualized in figure 27 and discussed in the chapter above, the number of negative RIO points increases with the Polar ice class. Figure 27 shows a higher concentration of negative RIO values in the Kara Sea and the Gulf of Ob. Thus, these operations are less relevant when it comes to transit voyages. Almost all the points are from two periods, one in 05-2021 and one in 06-2016. Both May and June are in the melting period (ref Figure 22), and the negative RIO can result from uncertainty in the ice thickness from the ice charts. However, the negative RIO values are calculated from actual ice conditions in the ice charts. Hence, the ice conditions are not assumed based on the worst-case as discussed earlier.

It is interesting to compare different route alternatives based on the historical data. At the begging of the NSR, a vessel can either take a northern route north of Severny Island or through the Kara Strait. There is often more sea ice in the summer season in the area east of Severny Island than in the northern part of the Kara Sea (10). This trend is also apparent in figure 27. Almost no vessels have operated in the Northern part of the Kara Sea with a negative RIO. On the other hand, the area between the Kara strait and the Vilkitsky Strait has vessels with higher ice classes operated with negative RIO values. All ice classes except PC6 have operated outside their limitations in the area around the Vilkitsky Strait. According to other reports about incidents and navigational handbooks, this is an area where vessels often have the most challenging ice conditions (10).

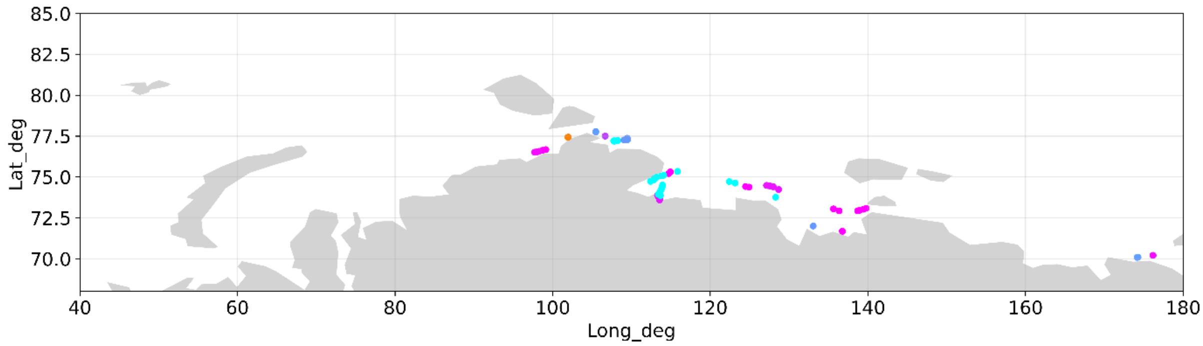
In the second half of the NSR (from longitude 120 to 180), there are fewer negative RIO values than in the western part. This can be because there is more traffic in the western part. However, there is a clear pattern for negative RIO values in the eastern and western parts. In the western part, there are 18 instances between week 30 and 52 where vessels operate with a negative RIO. In the east region, seven cases have been found where a vessel has been outside its operational limit. When ice classes are compared for the same areas, PC6 and PC7 vessels account for 71% of all the negative RIO values in the area. On the other hand, IC and NIC ice-class vessels accounted for 54% of all the negative RIO values in the eastern part. Thus, based on historical data, vessels with lower ice classes will more often be surprised by challenging ice conditions in the East region. The result is high RIO values outside the operational limit. The increased RIO values can also be a consequence of the difficulties in predicting ice conditions for longer voyages, where old drift ice can result in negative RIO values.

Historical RIO values 2014-2021 for the NSR (IMT/kystverket)

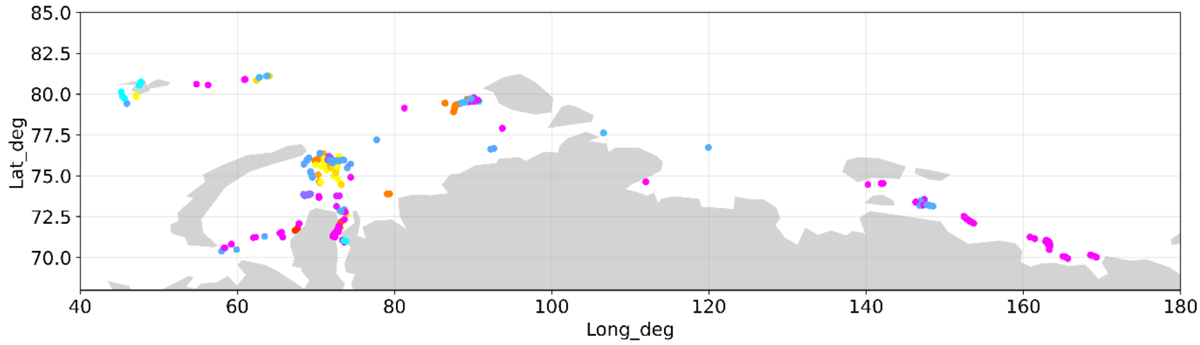
Not ice-strengthened



IC



PC6



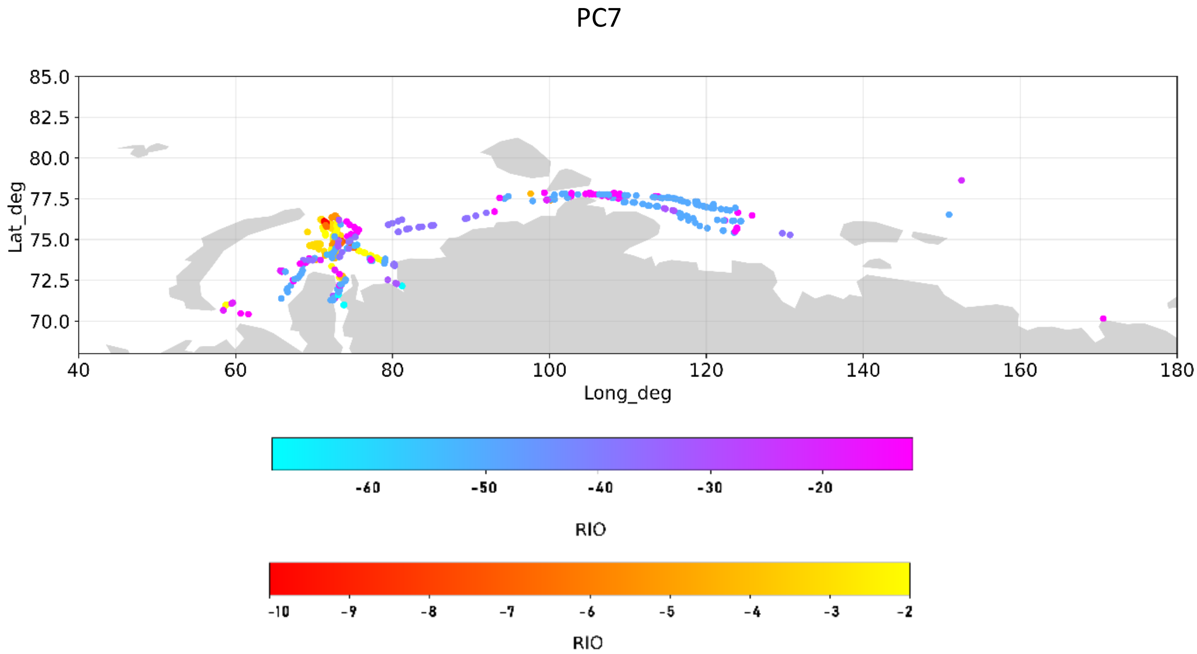


Figure 27: Historical RIO values for vessels in the NSR 2014- 2021. The data is not adjusted for vessels under ice breaker escort.

5.1.2 Speed evaluation

Polaris Recommended speed limits for elevated risk operations. Hence, it is understood that ice conditions play a significant role in the speed a vessel can operate under the given ice conditions. This relation has also been documented by Panchi (12) for the Kara Sea, where RIO values showed a correlation between RIO values and speed. Panchi identified a general increase in the RIO as the speed increases. However, it was summarized that a dependency was found, despite the RIO not being directly linked to the speed. Therefore, it is interesting to study if this dataset has a similar correlation between sog and RIO values. The RIO and speed were plotted for both datasets and each ice class. The results were plotted as a boxplot with a curve fit for the regression line.

Figure 28 shows the plot. The results showed little coloration between the speed and the RIO. The Pearson product-moment correlation coefficient (PPMCC) was calculated using Scipy in Python. The PPMCC between the RIO and sog is 0.30. Hence it is a small correlation. However, there is a more significant correlation for RIO values > 0. For this range, the speed reduced with 0.24knots/ RIO value, and the PPMMC was 0.38. This result is similar to what Panic found in his study. On the other hand, for RIO values < 0 is the PPMCC 0.08 between the RIO and the sog, and it is difficult to conclude that a correlation between the speed and the RIO exists. It can be argued that the correlation for the entire dataset exists because it is mainly positive RIO values in the dataset. Thus, the lack of correlation between negative RIO values negatively impacts the overall PPMCC little. This trend can also be seen in figure 28 for the negative RIO values, where the negative RIO values derivates from the regression line.

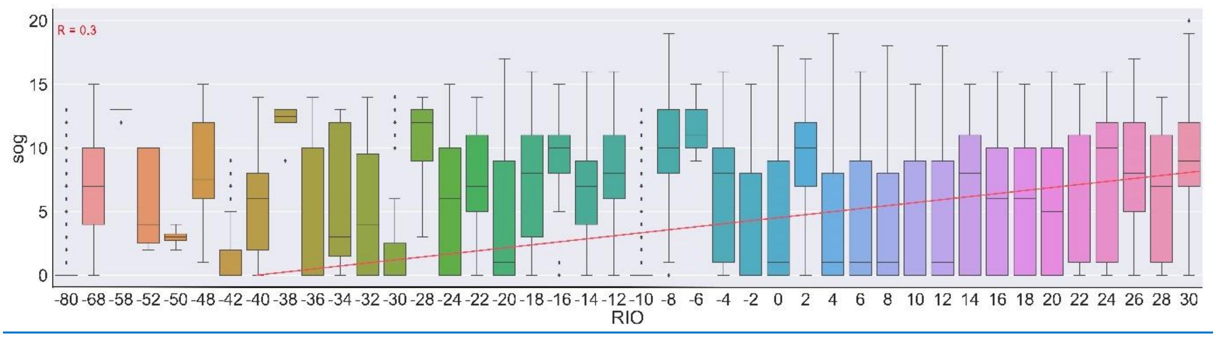


Figure 28: Boxplot of RIO and speed for all RIO values from the IMT/Kystverket database

It is difficult to explain why there is no clear trend for the negative RIO. One reason may be that the negative RIO value is due to the poor resolution of the ice charts. Lower resolution will result in incorrect RIO values related to what the master experiences/calculate in the situation. Hence, the speed will not be reduced. Another explanation could be that the calculated RIO values are when an ice breaker escorts a vessel. To further investigate, can it be advantageous to combine RIO values along an actual voyage with ice maps and satellite images and filter out operations with an ice breaker.

5.2 Combined analysis

It is interesting to see how the different methods variate by combining them in a new plot. Figure 29 combines AIS data for a vessel with no ice strengthening, a satellite image from the Sentinel – 1, and ice chars for the same period. Based on the RIO calculation, the vessel operated with an RIO of -47 when it was sailing through the blue area. IMO categorize this voyage as an operation subject to Special Consideration mean operations whereby extreme caution should be exercised by the Master and officers in charge of a navigational watch when navigating in the sea ice (2). However, the sog was constant during the voyage. Figure 29 shows that it can reduce the theoretical RIO by sailing north of the blue area. However, it can be assumed that the master instead sailed through the blue area using one of the openings seen on the satellite image, corresponding to a higher RIO value.

Regarding the ability of an ice chart to predict and visualize the actual ice conditions, figure 29 shows the difference between an ice chart and actual ice conditions. For example, the blue area on the ice chart corresponds to 7/10, and 8/10 has a lower density of ice north of the sailing path. However, the ice analyst has assumed equal concentration for the whole area. Another area of interest is the lower right corner, where the actual vessel is marked with a pin. Since the ice concentration given in the ice chart is zero, the calculated RIO from the ice chart will be 30. Still, as seen on the satellite image, there are areas with higher ice concentrations. Therefore, it can also be assumed that the vessel that sailed through this area with higher ice concentration.

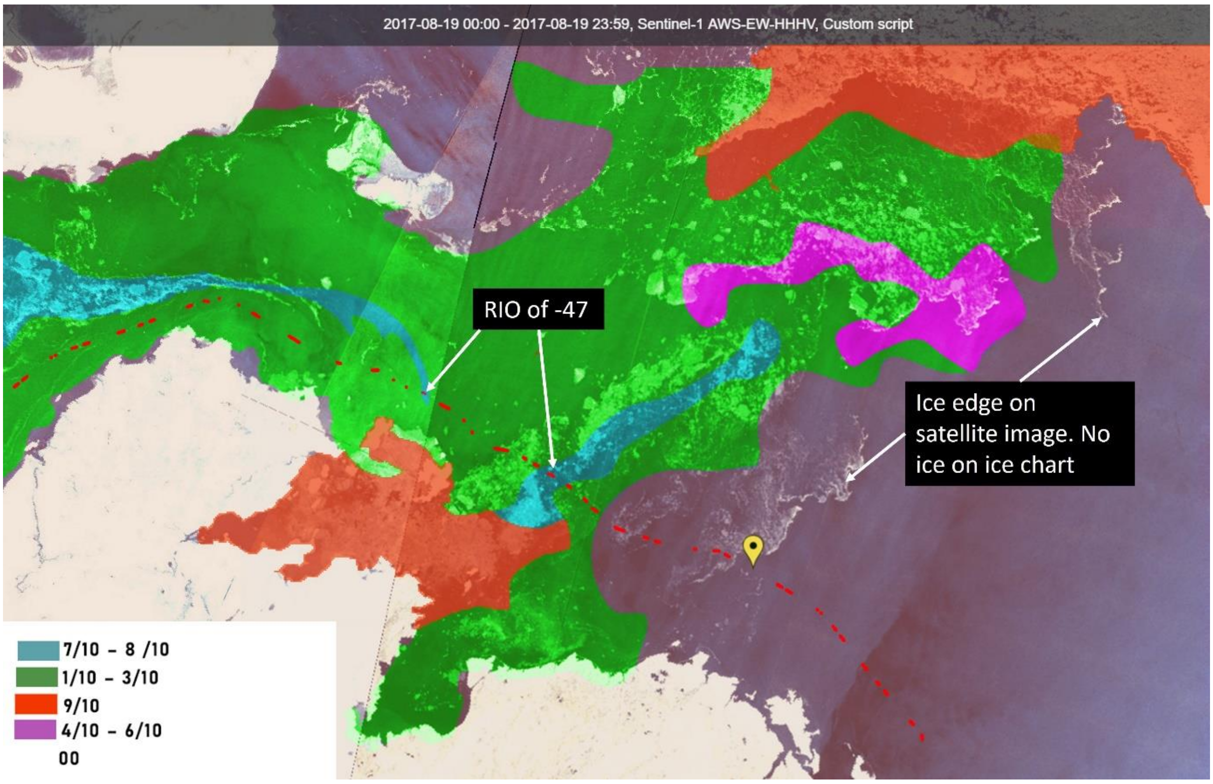


Figure 29: The sailing path from AIS- data marked with red, vessel located with satellite image marked with a yellow arrow, and ice chart overlayed where the different colors represent different ice concentrations. Additional coments for ice edge did not show on the ice chart and where the RIO was calculated to -47. The ice chart and satellite image were taken on 19 August 2017.

It is interesting to study an ice channels impact and how this affects the results. An area where the author assumed it could be an ice lead was looked at in more detail. Figure 30 shows a vessel with a PC7 ice-class operating without an icebreaker. However, this is a highly trafficked stretch which often results in an ice channel. The channel can be seen on the satellite image (both the main and the zoomed-in black). The calculated RIO for the voyage is 0. The voyage marked with red dots is in medium first-year ice with a concentration of 10/10. According to IMO regulation, can the vessel operate under these conditions. However, when comparing the ice conditions from the ice chart with the actual ice conditions from the satellite image, the ice chart cannot visualize the ice lead. Thus, the ice chart's resolution seems too low to include information about this important phenomenon. The ice cart generalizes these conditions, resulting in a higher theoretical RIO than the actual risk. It also seems that the area where the ice chart shows medium first-year ice includes smaller areas of thick first-year ice. Operations in these areas will result in an RIO of -10 for a PC7 vessel. According to IMO regulations, will this result in an elevated operational risk and the recommended speed limit is 3 knots.

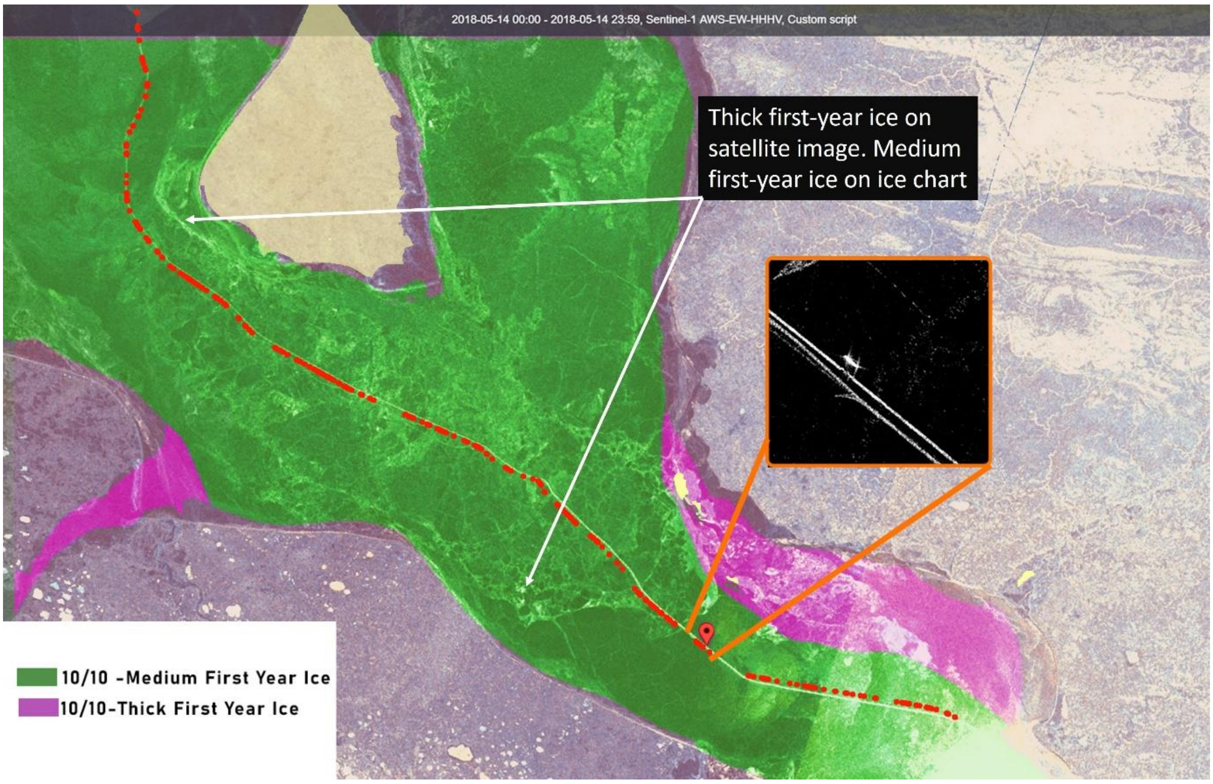


Figure 30: The voyage along an ice channel from AIS- data marked with red, vessel located with satellite image marked with red arrow, and ice chart overlayed where the different colors represent different ice concentrations.

5.3 Polaris for planning purposes

A predictive model is used to evaluate a predefined route based on historical data to investigate how Polaris can be used for planning purposes. The performed simulations calculated RIO values for the last eight years (2014 to 2021) for all ice classes lower than PC7.

5.3.1 RIO predefined route

To better understand the operational risk along the predefined route, the mean RIO during a year is plotted in figure 31 for a PC7 vessel. The western part of the NSR has the most favorable conditions with the lowest risk. Compared to the previous simulations, this was expected. The first part with elevated risk is the area around Servernaya Zemlya, known for fast ice and ice rivers. Tadeusz Pastusiak refers to this area as the single most important straits to determine the duration of the navigation season for transit navigation on the NSR. The area becomes blocked by the systematically growing ice cover or when a blockage occurs, representing the end of the season. (52), The Sannikov Strait, is the only part of the route with a negative median RIO. The area is known for its fast ice. Vessels with a maximum draft of 8m can use the strait closer to the mainland. This area generally has less ice. Hence higher RIO values.

The Sanikov strait, according to Appendix B is freezing up after Servernaya Zemlya, and is therefore rarely the limiting factor for vessels with lower ice classes transiting. Lastly, the eastern part of the NSR has a relatively high RIO compared to the more challenging parts. This part of the NSR is known to freeze after Servernaya Zemlya and open earlier (10). The results in figure 31 establish that the parts with elevated risk are often located where there are few other route options. Hence, the area with elevated risk is difficult to avoid or find better route options. Thus, the analyses along the predefined route will represent the actual problem. Other publications on sea ice density along the NSR have shown similar results.

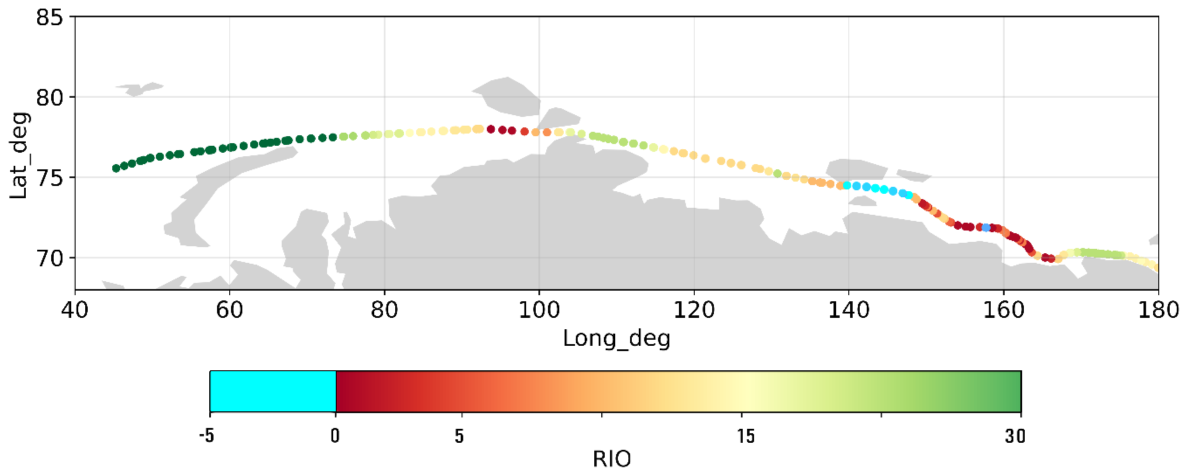


Figure 31: Median RIO values along a predefined route for a PC7 vessel. The median is calculated for data from 2015 to 2021 with actuall ice condition values.

5.3.2 POLARIS as a decision/planning tool

POLARIS can also determine whether a vessel can operate or not based on historical data. Chapter 2.1 states that the areas with the highest statistical risks are narrow straits limited by land or solid ice. Therefore, it is interesting to analyze how the risk changes during the freezing phase for different ice classes. This analysis can further be used as a support tool to plan a voyage or determine the ice-class necessary to operate in a specific week. The porous is also to see how the RIO can vary within the same week. Figure 32 presents the week where the RIO in the lower quartile in a box blot with standard quartiles exceeds the POLARIS limitation. Hence, this allows extreme RIO values for one year and helps filter out uncertainties related to the ice charts.

Table 18 shows an overview of the operability of a vessel with a given ice class. The most significant changes happened between class C, class B, and PC7 vessels. Class C vessels' allowed time to operate without an ice breaker varies between week 40 and 44 and is within what can be expected, 1-3 weeks. The difference between No ice-class (NIC) and IC vessels in terms of operability is small, and the only change is one week for operations without an ice breaker. On the other hand, an IB ice-class vessel will extend the period when it can operate without an ice breaker for three weeks and with an ice breaker for eight weeks compared to an IC vessel.

Comparing class C and class B vessels shows an apparent increase in operability for vessels operating without an ice breaker. IA vessels will exceed the POLARIS operational limit for operations without ice breakers in week 48. However, as seen in figure 33, only one point exceeds the limit with an RIO value of -1. If this point is disregarded, the period will be extended to week 50, a six-week extension of the season compared to IB vessels. Suppose the one value in week 48 is disregarded. Will an IAS vessel extends its operational limit to one week for operations without an ice breaker and two weeks with an ice breaker. When class B vessels are compared to the class C vessels for operations with an ice breaker, the season will be extended by 8-10 weeks.

Chapter 2.4 states that PC7 vessels can operate with RIO values between 0 and -10 if the speed is reduced to 3 knots. However, an ice breaker will not operate with a 3-knot speed limit. Therefore, it can be questioned if the vessel can extend the season to week 4. For operations with no limitations can, both PC7 and IAS vessels operate during week 51. The main difference is PC7 vessels can operate until week 3 with reduced speed and no icebreaker. Still, an IAS can operate until week 2 with icebreaker assistance.

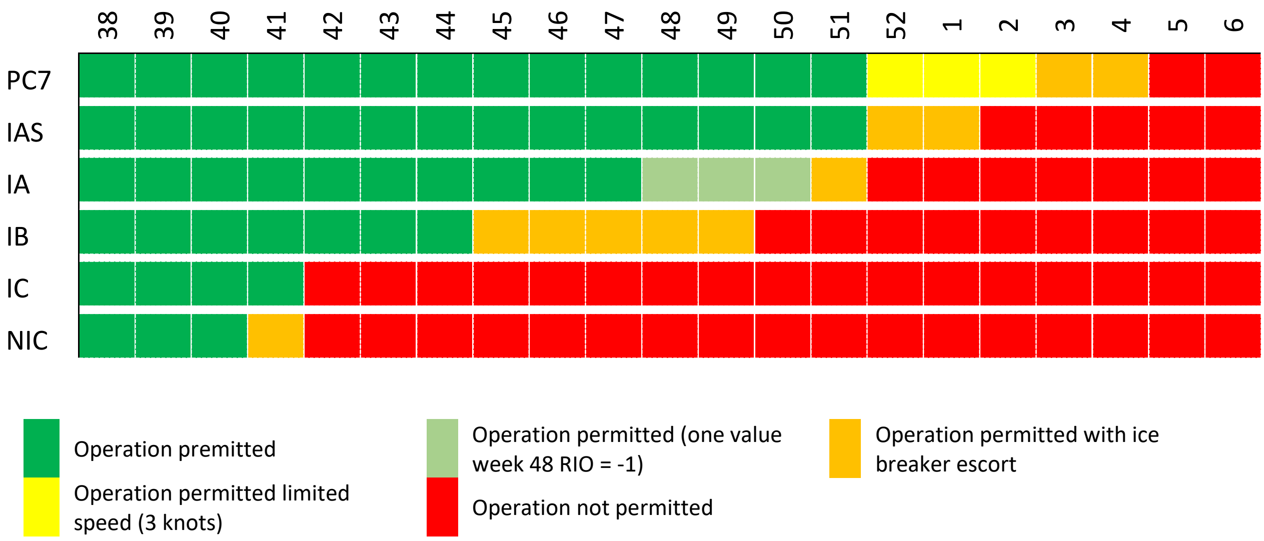


Figure 32: Gantt diagram of operability calculated for the predfined route for diffrent ice classes. The number represent the week number.

	RIO > 0	RIO > -10	RIO > -20	RIO < -20
PC7	51	2	4	5
IA Super	51	1	2	5
IA	47 (50)	51	52	3
IB	44	49	51	52
IC	41	41	50	51
NIC	40	41	44	45

Table 18: Ice classes and the week it can operate before it exceed the RIO range. The numbers represent the week number.

The boxplot plot visualization shown in figure 33 shows the RIO values for the NSR based on ice charts from 2014-to 2021. Boxplots for relevant weeks and the IA Super ice class are listed in appendix B. These plots give a more detailed analysis of the risk picture along the predefined route int the NSR and when or where it starts to freeze. The outliers marked with a diamond shape indicate the points that differ significantly from the other observations. The outliers on the lower side can often be identified as areas of drift ice or earlier sea ice development than usual. The outliers on the upper side can present seasons with less ice than average. The point around 180 degrees is an example of a small area of multiyear drift ice derivate from the RIO values in the area. This case was further examined with satellite images, and it was clear that the ice represented a smaller area and was possible to navigate around. The outliers should therefore be compared to other RIO values in the same area. It can also be wise to compare it to the plot for the next week to determine if it is drift ice.

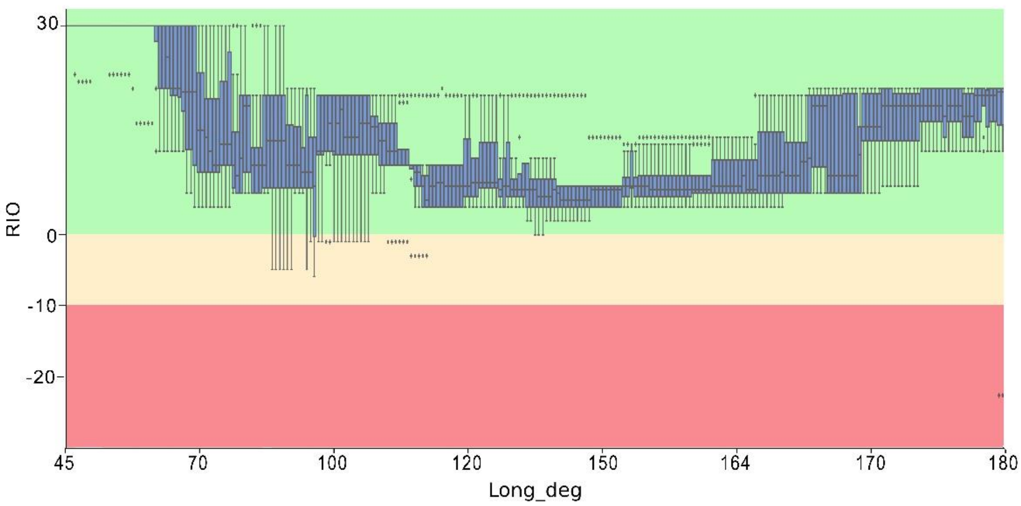


Figure 33: Boxplot of the RIO along the route for week 48 and ice-class IA. The one value of -1 can be seen at around 100 degrees East. The x-axis is converted from the time domain to longitude.

5.3.3 Route summary based on POLARIS

Polaris is intended to be used as a decision support tool. Figures 34 to 39 provide a route summary based on the planned route proportion corresponding to each of the POLARIS RIO operational limits. The results in Figures 34 to 39 are based on median RIO and information from table 3. In combination with the result presented in the previous chapter, Figures 34 to 39 gives a better risk picture of what can be expected along the route for a given week. In this case, if a vessel with an IC ice-class plan to execute the predefined route in week 46, it can expect that roughly 20% of the route may require an ice breaker, and the other 80% is in the permitted operational region. It is interesting to see how the result will change if a planned voyage changes from week 46 to 47 or 46 to 45. In the first scenario, will the postponed voyage increase the expected use of an ice breaker from 20% to 55%, and only 45% of the route can be operated without an icebreaker. On the other hand, if the voyage is moved one week earlier, the expected use of icebreaker escort is reduced to 2%.

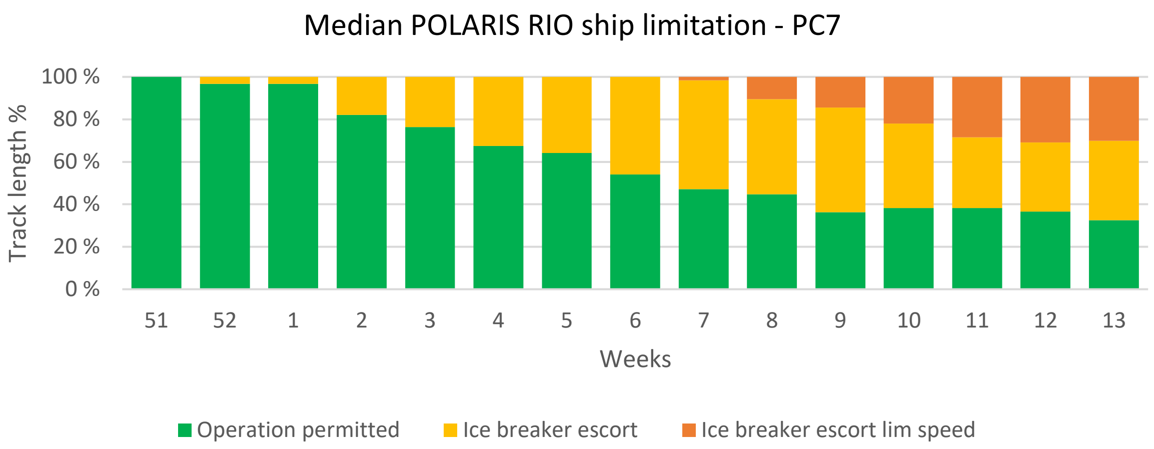


Figure 34: Median RIO for the predefined route for a PC/ ice-class vessel.

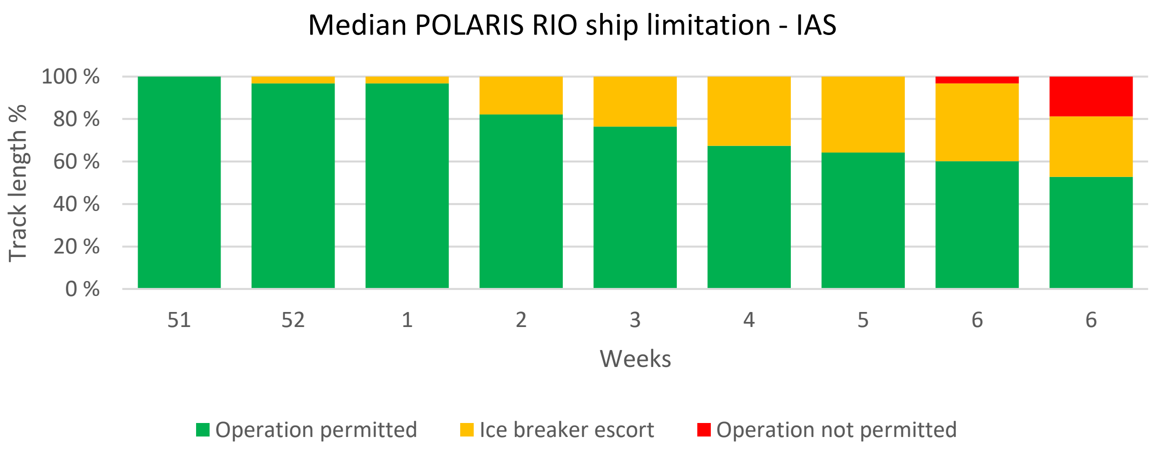


Figure 35: Median RIO for the predefined route for an IAS ice-class vessel.

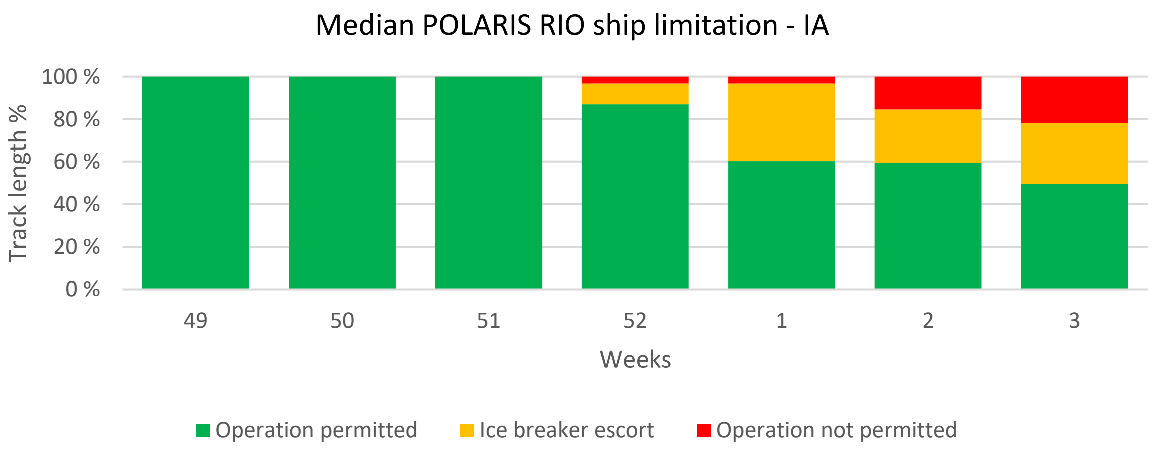


Figure 36: Median RIO for the predefined route for an IA ice-class vessel.

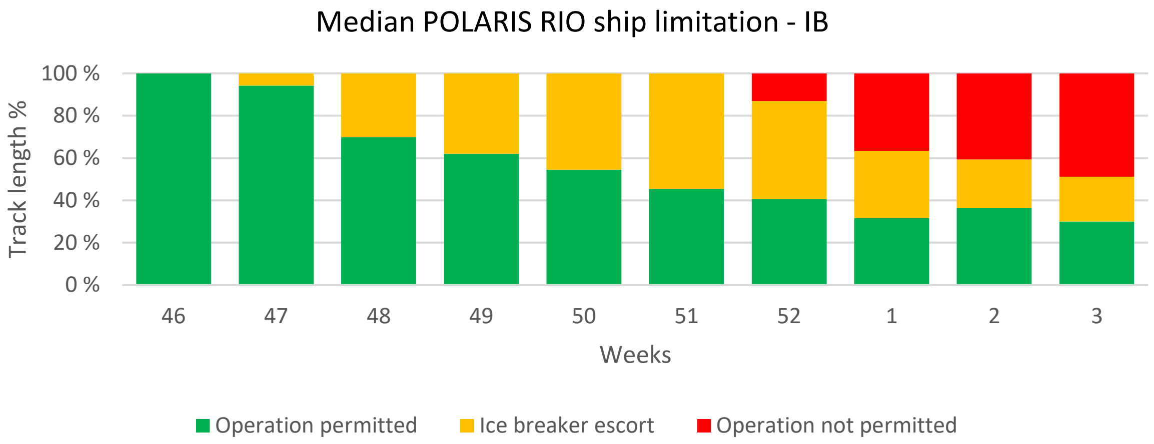


Figure 37: Median RIO for the predefined route for an IB ice-class vessel.

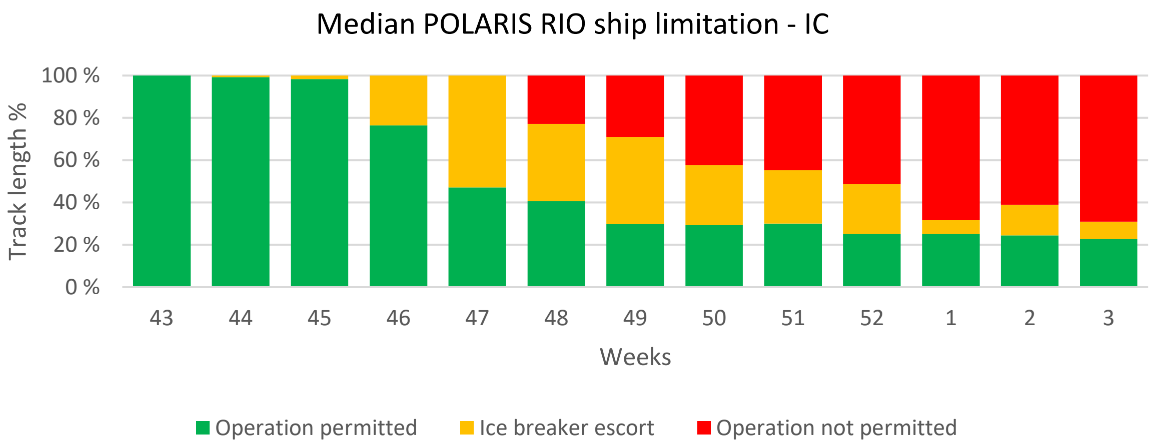


Figure 38: Median RIO for the predefined route for an IC ice-class vessel.

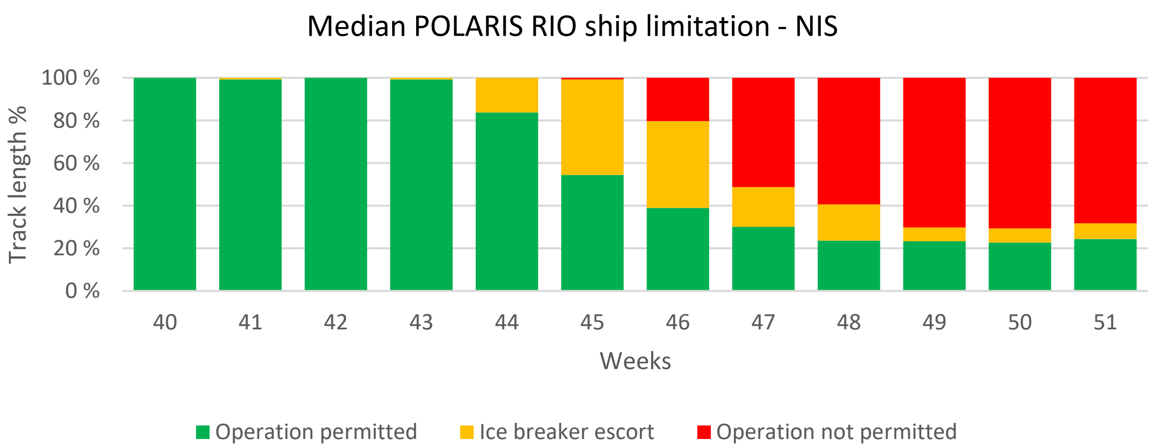


Figure 39: Median RIO for the predefined route for a NIC ice-class vessel.

5.3.3 Operational predictions compared to old operational rules

The operational limits calculated over can be compared to the old go/ no go rules for the NSR. DNV advised using these rules to validate the result calculated from POLARIS. The old operational rules for the NSR were recommended since there is limited experience in using the new regulations. The old rules categorize ice as heavy ice conditions, medium ice conditions, and light ice conditions. According to these regulations, a Class C vessel can only operate until the 15 of November (week 46) or when the area is covered with < 30% first-year medium sea ice. Class B vessels have the same limitations for first-year ice after week 46 (53). Note that the rules do not define the severity of the ice conditions. Instead, it requires “The Authorized body or its subordinate organization” to post on their website about the “ice forecasts 72 hours in advance related to the water area of the Northern Sea Route including the forecast of assessing of the types of ice conditions "heavy", "medium", "light", "clear water" for the areas of the water area of the Northern Sea Route” (6) .The Ice conditions mentioned above were converted based on regulations from the NSRA. The corresponding ice regimes were then used to calculate an RIO that was set as an operational limit. The calculated operational limit is compared to the regulations in Table 2. The result is listed in Figure 40. The recommendations are similar for operations without an ice breaker (+/- 2 weeks). There is a clear trend for operations with ice breaker escort for higher ice classes (> IC) where the POLARIS extends the operational season by up to 6 weeks.

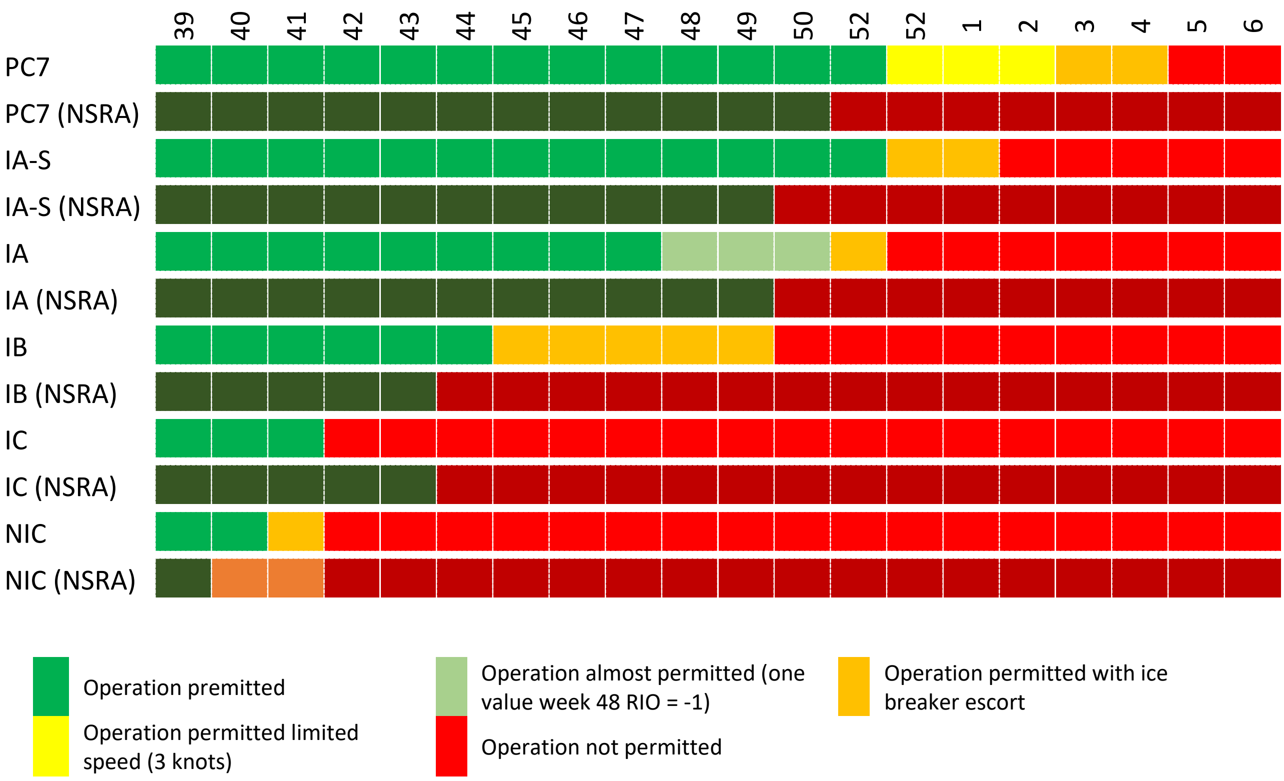


Figure 40: Gantt diagram of operability calculated for the predfined route for diffrent ice classes. The number represent the week number. (NSRA) ice classes is the operability based on the old NSRA rules.

	Operability based on POLARIS	Operability based on POLARIS, with an ice breaker	NSRA old rules	NSRA old rules, with an ice breaker
PC7	51	4	50	50
IA Super	51	1	49	49
IA	47 (50)	51	49	49
IB	44	49	43	43
IC	41	41	43	43
NIC	40	41	39	41

Figure 41: Comparison of the operational limit calculated with POLARIS and the old NSRA rules.

6.0 Limitations

In order to use historical data to predict the operational risk for a vessel with a lower ice-class transiting the NSR, a method only considering POLARIS is used in this work. However, there exist multiple ways to evaluate the operational limit. If multiple methods give similar results, it increases the certainty of the result. The analysis is based on open-access ice data from AARI, Vessel ice classes from NSRA, and satellite images from Sentinel-hub. The AIS data from ASTD and IMO/Kystverket are not publicly available. Here, special permission must be granted. If errors in the data are not discovered, this will impact the outcome of the simulation.

6.1 Data input

Only one open-access source is available for the ice chart, including the stage of development and concentrations. Thus, validating and comparing the data to other sources is not easy. The only suitable method found has been to compare it to satellite images. This method works well for concentration but is more difficult to use for development. The ice chart is the most important limitation of the model. When analyzing historical risk, it can be argued that the low resolution on the ice charts results in errors and extreme values. An example where it is clear that the resolution is too low can also be seen in Figures 29 and 30. Other limitations of the ice chart are the update frequency which is limited to once a week, and the limited data available during the melting period. When RIO values were calculated for historical data, the ice chart with the closest ice data was used. Other studies have instead used only the AIS data from the same date. However, as seen in figure 26, there was no coloration between the days to the closest ice chart and negative RIO values. This coloration is perhaps a result of the already low resolution on ice charts. The model also assumed the worst possible ice conditions where there was no information in the ice chart. However, since little information is available from the melting period, all the calculations resulted in extreme values that do not represent the actual risk.

Two AIS databases have been used, and both have limitations. IMT/Kystverket are limited by the re-visiting time, leaving gaps along the route. ASTD, on the other hand, is limited by the filtered sample rate where the bias increase with speed. However, the deviation between the two datasets determines the location. Thus, the accuracy of the positions is good. Other limitations with the data from ASTD are the shipid which changes each month, and many data points do not include information about the ice class. Therefore, the IMT/ Kystverket database was the preferred AIS input in this model.

The only open-source database linking ice classes and IMO numbers are the NSRA database. This database has also been used in other studies in the NSR. However, chapter 4.1 indicates that this method is insufficient for vessels with lower IMOC? / FinNICh- Swedish ice classes. If lower ice classes must be converted from IMOC? / FinNICh- Swedish ice classes to Russian ice classes and back again will result in errors, on average, 20% of the ice classes will be wrong. Instead, another database like SeaWeb should be used for non-Russian vessels.

6.2 The model

The model works as a POLARIS RIO calculator, and it is essential to consider the input when calculating to obtain good results. There were mainly two problems the model had to deal with where data was reported as “unknown”. The first was when the data for the stage of development or the concentration of sea ice was missing. This challenge is discussed in detail in chapter 4.3. The second was when the ASTD database did not include the ice-class for the vessel. Only 15% of the vessels were assigned an ice-class, and for the period 2017-2019 + 2021 were no vessels assigned an ice-class. Two options were considered:

- Skip the calculation for the given data point.
- Assume the worst outcome (No ice class, highest possible concentration, and heavy multiyear ice).

Both methods were considered. Data from chapter 4.1 could be used to analyze if the assumption to assign no ice-class is sufficient to determine the ice classes. It was clear that this data should be skipped instead. As discussed earlier, the main challenge with the ice data is when the ice melts and satellites cannot determine if it is a melting pod or the ocean. However, assuming multi-year in this case will not represent the actual ice conditions. It was therefore decided also to skip these calculations. It results in a model that does not work well in the melting period between weeks 20 and 30.

When historical AIS data is used to calculate RIO values it is essential to control if a vessel is escorted or not to determine the right RIO. However, this model cannot determine if a vessel is escorted or not. There is a different reason why this has not been done. One reason is the incomplete ice-class information for the ASTD database. This limitation makes it necessary to combine another AIS database with ice-breakers information. There is possible to get the information from the IMT/ Kystverket database. However, more complex detection methods must be used than what has been used by Nabil in earlier and similar studies. Therefore, the author focused on extreme historical RIO values outside the operational limit, both with and without ice breaker escort. Hence the RIO value is outside the operational limit with and without an ice breaker.

In chapter 5.3, it is of interest to aim for the route with the least ice when choosing a route. Hence, an optimization algorithm/method determining det optimal route is better to use than a predefined route approach. This optimization method could potentially result in longer operational seasons than the results in chapter 5.3. However, simulations considering more than one year will give a more extensive basis to find the operational period.

7.0 Conclusion and further work

7.1 Conclusion

This thesis has investigated cargo vessels with lower ice-class transiting the NSR and their operability from a risk index perspective based on Polar Operational Limit Assessment Risk Indexing System (POLARIS). International Maritime Organization (IMO) recommends POLARIS as an acceptable methodology to determine a set of operational limitations in ice. Despite limitations, POLARIS is “a pillar in the overall decision process of various stakeholders such as classification societies, underwriters, and shipowners” (1). This research aimed to identify: *to which degree POLARIS, based on available ice information, can be used for planning purposes?.* A comprehensive review of research on the development of POLARIS, the use of satellite images to analyze ice conditions and vessel detection, and the theoretical background for relevant data sets were carried out. The following conclusion summarizes the most important aspects of each part of the thesis.

In the first part of this thesis, a validation study of relevant data input for ice conditions, AIS data, and ice classes was conducted. This part was considered essential to determine to which degree historical data can be used in POLARIS for planning purposes. Converting ice classes from the open-source database from NSRA resulted in the wrong ice classes for 20% of the vessels compared to what was assigned by the classification societies. For AIS data, the IMT/Kystverket and ASTD datbases were compeared. The IMT/ Kystverket showed the best result with the highest resolution. The lack of data in the melting period was established for ice conditions, making it challenging to calculate RIO values during this period.

In the second part, RIO calculations based on historical data were presented. Vessels with lower ice classes were in 99,45% of the AIS messages collected operating within their RIO limits. This work established a link between the operational risk, the number of days to the closest ice chart, and speed based on RIO calculations from the developed model. From this link, no distinct trend or correlation was identified between the number of days to the closest ice chart and the operational risk. A trend was identified between the speed and the operational risk picture for the speed. However, no correlation was identified for the negative RIO values. Areas of extra interest were determined based on where vessels with different ice classes had operated with negative RIO values. Lastly, analyses combining Ice charts, AIS data, and satellite images were conducted for two voyages where the vessel had operated with negative RIO values. This study indicates that the model's limiting factor is the ice charts' resolution.

The last part, a predictive method for forecasting a vessel's operational limitations for a given week, was developed based on a historical AIS route and ice charts. First, the most challenging areas were established based on median RIO values for a whole year. Second, the operational limits for the freezing period for different ice classes were investigated, and a forecast for when a vessel with a given ice-class could operate with or without an ice breaker was established. Lastly, the operational limitations for each week were analyzed by investigating how much of the route a specific operational limitation could be expected.

The results indicate that POLARIS calculated from historical AIS data and ice charts do not necessarily reflect the actual risk level of the master experience. As mentioned above, the resolution of the ice charts is the limiting factor when RIO is calculated from historical data. When POLARIS is used as a tool to predict operability based on average ice conditions, the importance of ice charts with high resolutions is reduced. This thesis's predictive model has shown promising results and a clear trend between the operational results and the old NSR rules. Hence, POLARIS could be used for planning purposes with the available historical data. The main achievement of the current work is the established methodology process where POLARIS is used as a tool to predict the operability of different ice classes in the freezing period. The development of this methodology establishes the basis for more comprehensive predictive simulations in the arctic region.

7.2 Further work

After working with this, there are limitations in the models that need to be addressed. In addition, several topics for further improvements and investigations have emerged. Possible pathways to continue the project include, but are not limited to:

- Given the amount of time spent coding the model and building the datasets, not enough time has been available to validate the method. However, the results could be enhanced by comparing the operational results in chapter 5.1 to AIS data and determining if vessels are following the recommendations. In addition, a cross-comparison study could be a possible way to evaluate and validate the model.
- As mentioned in the discussion, all vessels with lower ice classes should get their original ice-class from another database instead of using the Russian ice classes from the NSRA database.
- The historical AIS data model could not detect whether a vessel was under an icebreaker escort. To have a model to determine this and if the risk picture according to POLARIS change is recommended. If the model can detect this, it can result in a better understanding of the data. For example, is it sufficient to add +10 to the RIO when a vessel operates behind an ice-breaker. The IMT/Kystverket databases should be used to detect if a vessel is escorted. A level 3 access for the ASTD database has very inconsistent data for the ice classes.
- Further analysis based on ice conditions from other sources should be executed. The analysis's most significant improvement can be made in the ice data. To compare the data, the RIO values be calculated based on data reported in ASSIST and investigate if there is a coloration between the two results. Another method could be to use satellite data to determine the ice condition where the ice conditions are updated with a higher frequency.
- Instead of using a predefined route when analyzing the operability of the NSR, an optimization algorithm could be used to determine the route with the lowest possible RIO. This improvement is especially relevant if the ice charts get better compared to today.
- There is also of great importance to investigate the risk picture based on POLARIS for different ice classes at the beginning of the season. However, there are limited tools today to determine the stage of development and distinguish between the ocean and melting pods.

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Appednix A – Java Code satellite images

Java code SAR image Ice vizualisation

Red =HH , Green= HV , Blue= HH

```
function overlay(top, bottom) {
  var res = -((2 * top - 1) * bottom- 2 * top) * bottom;
  return res;
}

function stretch(arr, min, max) {
  var delta = max - min;
  var offset = -min / delta;
  return arr/delta + offset;
}

function gamma(arr, val) {
  return arr ** (1.0 / val);
}

var mhv = Math.sqrt(HV + 0.002);
var mhh = Math.sqrt(HH + 0.002);
var ov = overlay(mhh, mhv);
var red = gamma(stretch(mhv, 0.02, 0.1), 1.1);
var green = gamma(stretch(ov, 0.0, 0.06), 1.1);
var blue = gamma(stretch(mhh, 0.0, 0.32), 1.1);
return [red, green, blue];
```

Code SAR image vessel detection

Cross polarization

Red = VV , Green= VH , Blue= VV

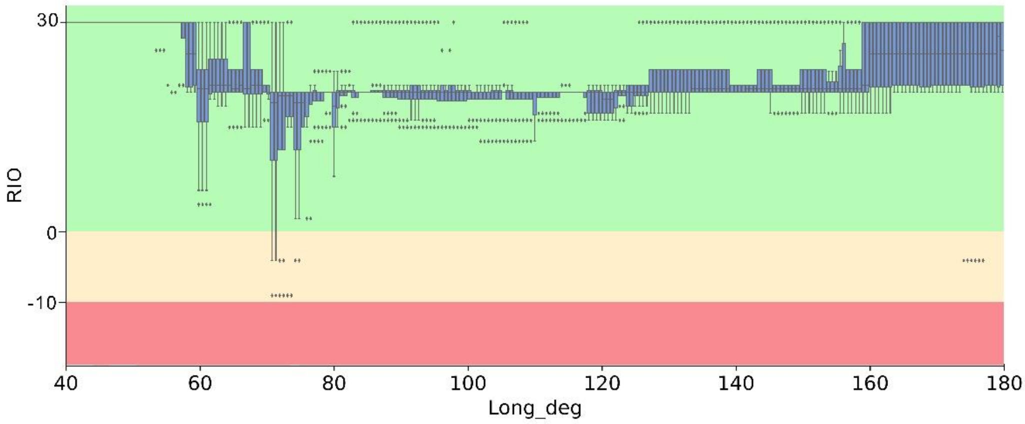
return [5.5 * VH > 0.5, VV, VH * 8];

return [red, green, blue];

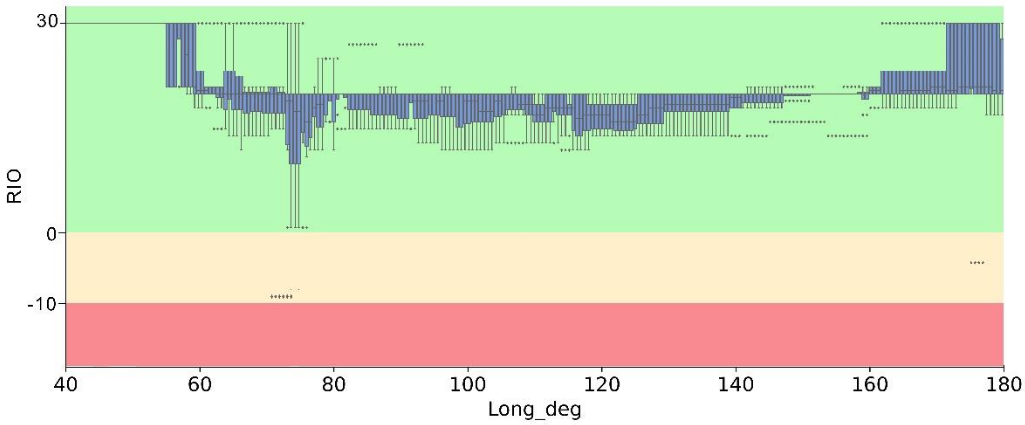
Appendix B – Boxplot predefined route

IA Super

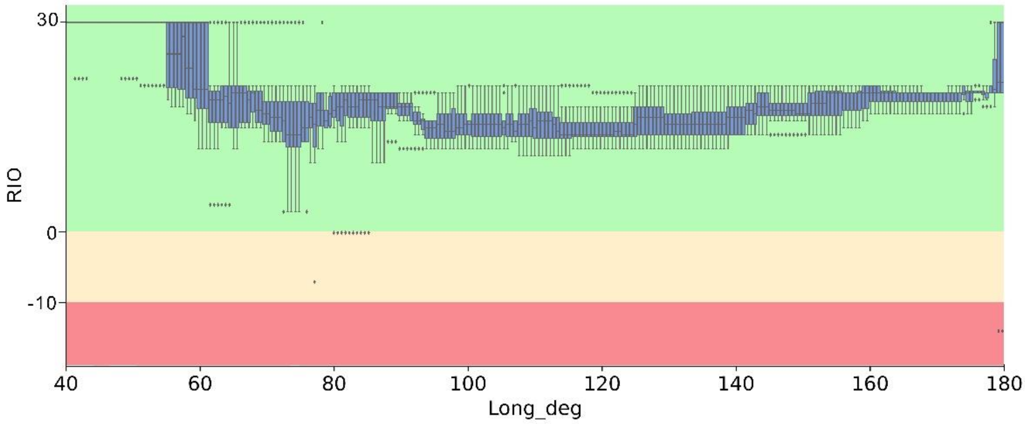
Week 45



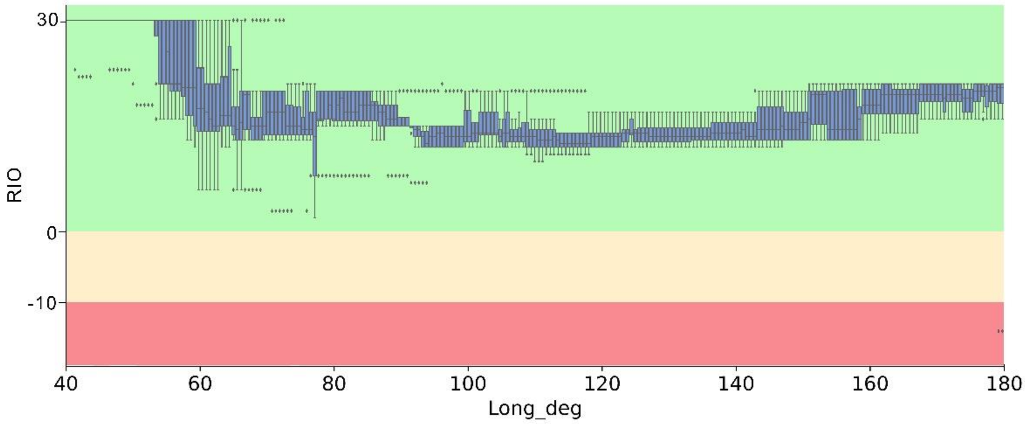
Week 46



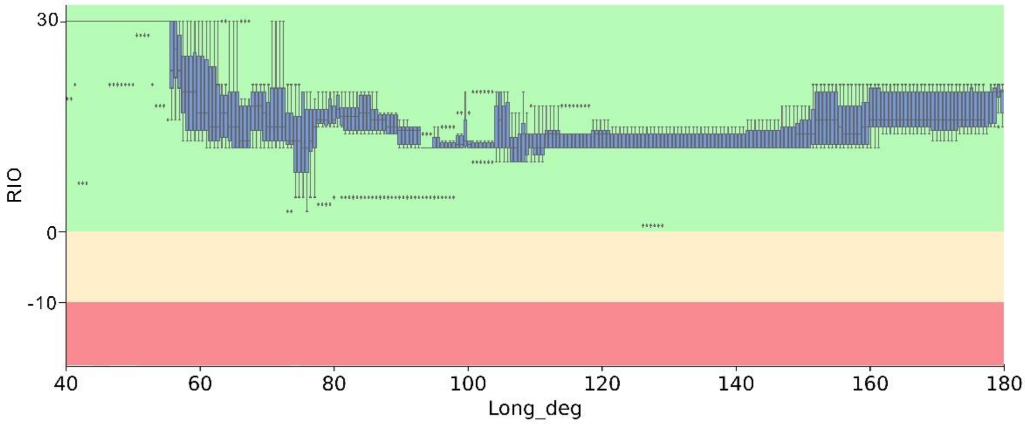
Week 47



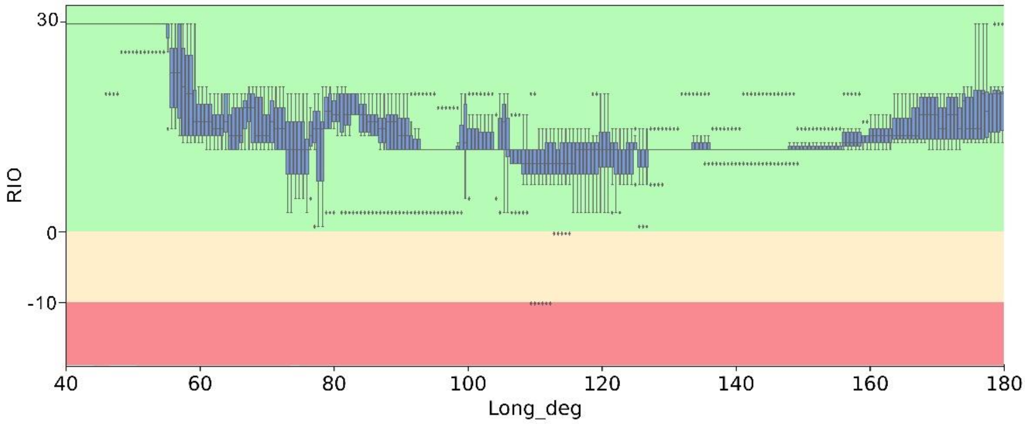
Week 48



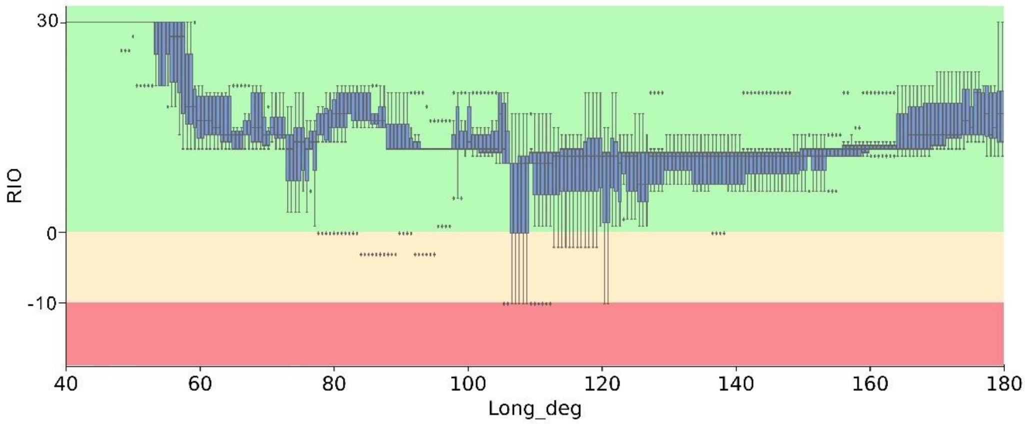
Week 49



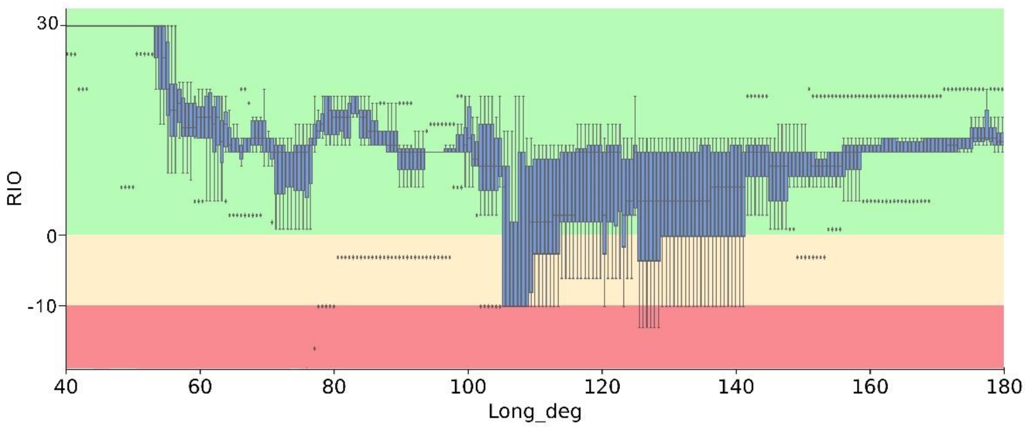
Week 50



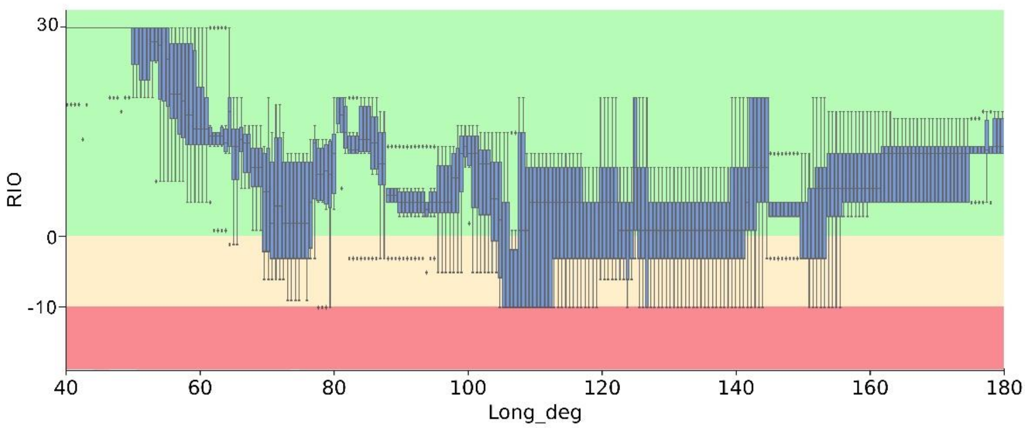
Week 51



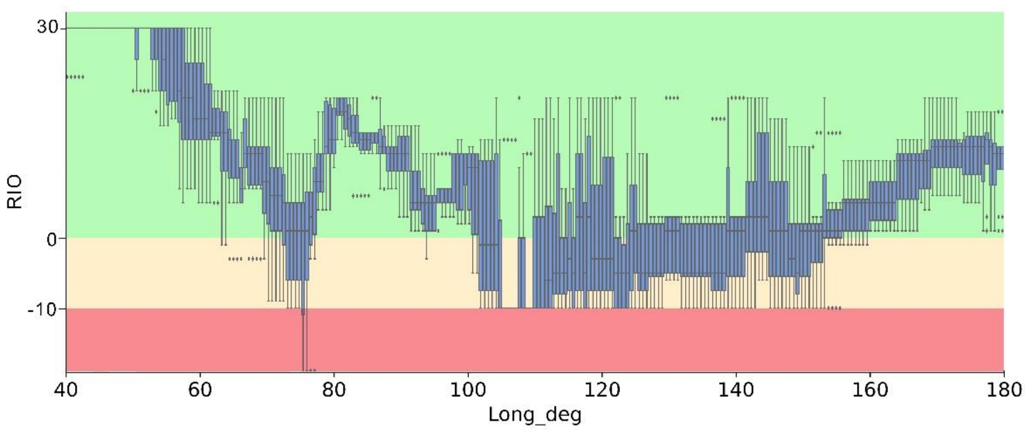
Week 52



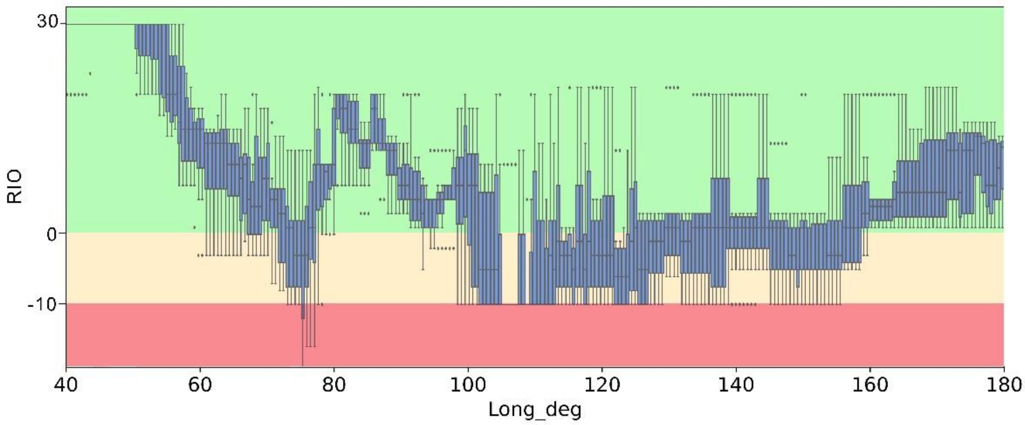
Week 1



Week 2



Week 3



Appendix C – Sigird 3

Appendix E - Code Tables for SIGRID-3 Variables

Table 1: Concentration codes for variable identifiers CT, CA, CB, CC, AV, AK, AM and AT.

Definition	Code Figure
Ice Free	98
Less than 1/10 (open water)	01
Bergy Water	02
1/10	10
2/10	20
3/10	30
4/10	40
5/10	50
6/10	60
7/10	70
8/10	80
9/10	90
10/10	92
Concentration intervals (lowest concentration in interval followed by highest concentration in interval)	
9/10 –10/10 or 9+/10	91
8/10 – 9/10	89
8/10 – 10/10	81
7/10 – 9/10	79
7/10 – 8 /10	78
6/10 – 8/10	68
6/10 – 7/10	67
5/10 – 7/10	57
5/10 – 6/10	56
4/10 – 6/10	46
4/10 – 5/10	45
3/10 – 5/10	35
3/10 – 4/10	34
2/10 – 4/10	24
2/10 – 3/10	23
1/10 – 3/10	13
1/10 – 2/10	12
Undetermined / Unknown	99

Notes:

a) When AV, AK, AM and AT are used, the total of the concentrations represented by the values for AV, AK, AM and AT must sum to the concentration represented by the value for CA.

b) When this table is used for concentration of ridges,rafting, snow cover, etc (ICERCN, ICEFCN, ICESCN, etc), the code value 98 is interpreted as "*no ridging/rafting/snow/etc*"

Table 2: Thickness of ice or stage of development codes for variable identifiers SA, SB, SC, CN, and CD.

Stage of Development	Thickness	Code Figure
Ice Free		01
Ice Thickness in cm	1-2 cm	02
	3 cm	03
	4 cm	04
	…	…
	50 cm	50
Ice Thickness interval, 5 cm	55 cm	51
	60 cm	52
	65 cm	53
	…	…
	95 cm	59
Ice Thickness interval, 10 cm	100 cm	60
	110 cm	61
	120 cm	62
	…	…
	190 cm	69
Ice Thickness interval, 50 cm	200 cm	70
	250 cm	71
	300 cm	72
	350 cm	73
Ice Thickness interval, 100 cm	400 cm	74
	500 cm	75
	600 cm	76
	700 cm	77
	800 cm	78
Brash Ice	Given by AV, AT, AM, AT in Table 3.3	79
No Stage of Development		80
New Ice	< 10 cm	81
Nilas, Ice Rind	< 10 cm	82
Young Ice	10 - <30 cm	83
Grey Ice	10 - <15 cm	84
Grey - White Ice	15 - <30 cm	85
First Year Ice	≥30 cm	86

Thin First Year Ice	30 - <70 cm	87
Thin First Year Stage 1	30 - <50 cm	88
Thin First Year Stage 2	50 - <70 cm	89
For Later Use		90
Medium First Year Ice	70 - <120 cm	91
For Later Use		92
Thick First Year Ice	≥120 cm	93
Residual Ice		94
Old Ice		95
Second Year Ice		96
Multi-Year Ice		97
Glacier Ice		98
Undetermined/Unknown		99

Notes:

a) This table has been extended to conform with the original SIGRID (1981) specification with two exceptions:

- Code 01 has been used to represent Ice Free instead of an ice thickness of 1 cm. To conform with S-57 standards, code 00 is not used. There is little significant difference between an ice thickness of 1 cm and 2 cm.
- Code 79 has been used for brash ice instead of a thickness of 900 cm as in the original SIGRID. The maximum ice thickness that can be reported by this code is therefore 800 cm instead of 900 cm.

b) When used for ICESOD, the two-digit codes in this table are repeated up to five times for each partial concentration. If a partial concentration is not used, it should be blank-filled.

e.g. 4 ice types present – So=98, Sa=97, Sb=86, Sc=81 : ICEAPC = 98978681*bb*
3 ice types present – Sa=97, Sb=86, Sc=81 : ICEAPC = *bb*978681bb
2 ice types present – Sa=96, Sb=88 : ICEAPC = *bb*9688*bbbb*
1 ice type present – Sa= 95 : ICEAPC = *bb*95*bbbbbb*

c) To differentiate dark and light nilas gradations, use stage of development codes ‘03’ and ‘07’ respectively.

Table 3: Form of ice codes for variable identifiers FA, FB, FC, FP and FS.

Form	Size/Concentration	Code Figure
Pancake Ice	30 cm - 3 m	22
Shuga/Small Ice Cake, Brash Ice	< 2 m across	01
Ice Cake	< 20 m across	02
Small Floe	20 m - <100 m across	03
Medium Floe	100 m - <500 m across	04
Big Floe	500 m - <2 km across	05
Vast Floe	2 km - <10 km across	06
Giant Floe	≥10 km across	07
Fast Ice		08
Growlers, Floebergs or Floebits		09
Icebergs		10
Strips and Patches	concentrations 1/10	11
Strips and Patches	concentrations 2/10	12
Strips and Patches	concentrations 3/10	13
Strips and Patches	concentrations 4/10	14
Strips and Patches	concentrations 5/10	15
Strips and Patches	concentrations 6/10	16
Strips and Patches	concentrations 7/10	17
Strips and Patches	concentrations 8/10	18
Strips and Patches	concentrations 9/10	19
Strips and Patches	concentrations 9+/10	91
Strips and Patches	concentrations 10/10	20
Level Ice		21
Undetermined/Unknown		99

Notes:

a) When used for ICEFLZ, the two-digit codes in this table are repeated up to three times for each partial concentration. If a partial concentration is not used, it should be blank-filled.

e.g.	3 ice types present – Fa=06, Fb=03, Fc=22	:	ICEFLZ = 060322
	2 ice types present – Fa=06, Fb=01	:	ICEFLZ = 0601*bb*
	1 ice type present – Fa-02	:	ICEFLZ = 02*bbbb*

Table 4: List of POLY_TYPE character variables

Land	L
Water – sea ice free	W
Ice – of any concentration	I
No Data	N
Ice Shelf / Ice of Land Origin	S

Table 5: Dynamic processes

Compacting ice, no intensity given	0
Compacting ice, slight	1
Compacting ice, considerable	2
Compacting ice, strong	3
Diverging ice	4
Shearing ice	5
Ice drift, rate 0,1 - 0,9 knots	6
Ice drift, rate 1,0 - 1,9 knots	7
Ice drift, rate 2,0 - 2,9 knots	7
Ice drift, rate 3,0 knots or more	9

Note: When actual rates of ice drift (ViVi) are given, code figure ViVi = 99 is used for rate unknown.

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